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STUDENTS' LEARNING EXPERIENCE IN THE CHEMISTRY LABORATORY AND THEIR VIEWS OF SCIENCE

In Defence of Pedagogical and Philosophical Validation of
Undergraduate Chemistry Laboratory Education



Hendra Y Agustian

A thesis submitted in fulfilment of requirements for the degree of
Doctor of Philosophy



**School of Chemistry
College of Science and Engineering
The University of Edinburgh
2019**

Dedication

I dedicate this thesis to the most important people in my life.

To my partner, Sid Madani, for his unfailing support, love, encouragement,
understanding, and camaraderie.

To my late father, Enoch Suryana, for his once word of wisdom:

“You don’t belong in this farm. Go and read a book.”

To my mum, Aam Maryam, for her love all through the decades.

To the children at the shelter Sanggar Anak Harapan in Jakarta, Indonesia, for their
energy and enthusiasm that motivate me to work in and for education.

Declaration

I declare that the thesis has been composed by myself and that the work has not been submitted for any other degree or professional qualification. I confirm that the work submitted is my own, except where work which has formed part of jointly-authored publications has been included. I confirm that appropriate credit has been given within this thesis where reference has been made to the work of others.

Edinburgh, 16th December 2019

A handwritten signature in blue ink, appearing to read 'Hendra Y Agustian', is shown on a light blue rectangular background.

Hendra Y Agustian

Abstract

Although laboratory work is often regarded as an indispensable part of modern science education, it was not until the latter 19th century that individual laboratory work became a common phenomenon in science courses. To date, science education, particularly on tertiary level, is thriving with both practitioners and researchers taking a closer look at laboratories in order to make the most out of its distinctive qualities and characters. Two of the most compelling cases for research and development in the context of undergraduate chemistry laboratory are students' learning and their views of the nature of science. In my research, I inquire into the various aspects of students' learning in the laboratory, particularly the preparation stage for laboratory work, and how they view science from an epistemological perspective. Results revealed salient features of learning attributed to pre-laboratory work, information management, and the affective domain. Pre-laboratory activities facilitate higher order thinking in the laboratory through learning goal setting. They also help students feel more confident with the experiments. Students use strategies to manage information during their laboratory work by chunking information in the form of pointers to consider, similar questions that are already answered on the online discussion forums, and by keeping an organised laboratory book. The evaluation of students' views of the nature of science suggests that the majority of students have either naïve or transitional level of understanding. Most of them are informed about the creativity and imagination in science. They also seem to subscribe to a dynamic view of scientific knowledge, in which ideas in science are regarded as tentative, provisional, and developing entities. Departing from this evidence, arguments for pedagogical and philosophical validation of undergraduate chemistry laboratory curricula were made and future directions for research and practice were identified.

Keywords: laboratory education, undergraduate chemistry, nature of science, pedagogical framework, philosophy of science

Lay Summary

Although laboratory work is often viewed as an important part of modern science education, it was not until the latter 19th century that individual laboratory work became a common phenomenon in science courses. To date, science education is thriving with both practitioners and researchers taking a closer look at laboratories in order to make the most out of its distinctive qualities. Two of the most compelling cases for research and development in the context of undergraduate chemistry laboratory are students' learning and their views of the nature of science. In my research, I investigate various aspects of students' learning in the laboratory, particularly the preparation stage for laboratory work, and how they view science. Results show that pre-laboratory activities facilitate higher order thinking in the laboratory. They also help students feel more confident with the experiments. Students use strategies to manage information during their laboratory work by chunking information in the form of pointers to consider, similar questions that are already answered on the online discussion forums, and by keeping an organised laboratory book. The evaluation of students' views of science suggests that the majority of students have either naïve or transitional level of understanding. Most of them are informed about the creativity and imagination in science. They also seem to subscribe to an idea that science is tentative. Departing from this evidence, arguments for pedagogical and philosophical validation of undergraduate chemistry laboratory curricula were made and future directions for research and practice were identified.

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Introduction

“We live in a society exquisitely dependent on science and technology, in which hardly anyone knows anything about science and technology.” – Carl Sagan (1934-1996)

The celebrated astrophysicist, author, and science communicator Carl Sagan laments over the above quote in his essay “*Why we need to understand science*” published in *Skeptical Inquirer* (Sagan, 1990). Therein he makes a case for understanding the underlying issues that permeate our daily life, such as global warming, acid rain, and toxic waste. Remaining ignorant about crucial issues like these is, in his words, a prescription for disaster. He also warns us about the danger of not being able to distinguish science from pseudoscience, especially when pivotal decisions that would determine the fate of a nation or the entire planet have to be made. Science is, according to him, much more than a body of knowledge. It is also a way of looking at and thinking about the world around us; about ourselves.

Sagan reflects on the context of science education in the United States in comparison with that of other countries such as Japan, Taiwan, Singapore, Finland, and Canada, in which America ranks lower in terms of standardised science and mathematics tests. He also compares students’ interest in science across educational levels, from kindergarten to university, which starts with a vigour in elementary school but gradually declines into despair in high school. We are flunking, he concedes.

Almost thirty years since this publication, the situation has not changed much. According to the Organisation for Economic Co-operation and Development (OECD) Programme for International Student Assessment (PISA), American students continue to rank around the middle of the pack in terms of science literacy, far behind many other advanced industrial nations (OECD, 2007, 2014, 2018). For example, in 2015, they were ranked 38th in mathematics and 24th in science among 71 participating countries, whilst Singapore, Japan, and Estonia topped the list (OECD, 2018). In terms of science performance, the UK was ranked 15th, the Netherlands 17th, and Indonesia was down below at 63rd.

In comparison to its American contemporary, science education in the UK is in a slightly better condition, at least in so far as PISA science results are concerned. For

instance, in 2015 students in the UK scored 12 points above the OECD average and comparable with students in Australia, China, Germany, Korea, the Netherlands, and Switzerland (OECD, 2018). This has been a stable performance since 2006. However, a review of a longer historical context of science education in the UK drawn from key government reports demonstrates that issues such as poor teaching quality and perceived lack of quality of science undergraduates are longstanding (Smith, 2010).

PISA in 2015 focussed on science assessment, on a rationale that science literacy is key to find the solutions to pressing societal and environmental problems, such as overpopulation and climate change. The test aims to promote a positive and inclusive image of science, so that all citizens, not only future scientists and engineers, can fully participate in and engage with a society that is increasingly shaped by science and technology. This is not only a rhetoric made by a supranational organisation such as OECD or UNESCO (2019). Several educational scholars have also called for the advancement of science *and* science education (Duschl & Grandy, 2013; Taber, 2017a). But more than just a seemingly obvious educational goal to attain, both PISA and academic scholars call for a science education that addresses not only knowledge *of* science, but also knowledge *about* science (Goff, Boesdorfer, & Hunter, 2012; McComas, 2002; OECD, 2007; Vesterinen & Aksela, 2012). By this line of reasoning, science education and science curriculum are built upon the corpus of knowledge generated by scientific research.

Apart from a realm of educational practice, science education is also a well-established field of research. It has its own idiosyncratic identity that is illuminated by and could be apportioned to other established fields of research such as history, philosophy, cognitive psychology, and sociology (Fensham, 2004). I argue that the wealth of knowledge in educational research, albeit its diffuse interests, also informs this field. Taber (2017b) describes that this field of scholarship is concerned with developing knowledge about the learning and teaching of science, in order to help us better understand educational problems such as why students often misunderstand scientific concepts, or whether students appreciate the affordances of chemical equations in laboratory and their relation to submicroscopic models of matter.

Just like science is composed of different disciplines such as physics, chemistry, and biology, so is science education research composed of its corresponding

elements. The principle of specialisation is at play here. A simple search of scholarly literature can therefore return distinctive fields of study such as chemistry education research and physics education research. Ideally, the practice of chemistry education should be built on and informed by chemistry education research.

Taber (2013) proposes a three-level typology of chemistry education research (CER), *i.e.* inherent, embedded, and collateral research, as a useful tool for researchers and authors considering whether a study or a research paper belongs to this field of scholarship. An inherent CER is concerned with issues intrinsic to teaching and learning chemistry, such as students' learning about glucose 3D structure, or teaching methods that can help a better understanding of reduction-oxidation. An embedded CER is concerned with a focus that is extrinsic to the field of chemistry education, but has been conceptualised carefully within chemistry teaching and learning. Topics on this level are, for example, peer assessment in the laboratory and incorporating higher order cognition into learning about the periodic table. Lastly, a collateral CER is concerned with a general educational focus that is linked with chemistry education, but the research questions are not strongly connected to anything particular to this educational context. The chemistry setting is, for instance, chosen because it provides a convenient albeit not an essential context.

This study belongs to both inherent and embedded typology. Essentially, it seeks to inquire into two distinctive lines of research. The first issue is students' learning experience in the chemistry laboratory. In particular, I am interested in understanding how they navigate through scientific concepts, laboratory-related skills, instructional information, curricular and pedagogical demand, and their affective domain. In Taber's framework of chemistry education research typology described above, this topic is extrinsic to the field of chemistry education, but it is highly conceptualised within chemistry education. Therefore, it operates on an embedded level. The second issue is students' understanding of the nature of science. I aim to understand how they view science and its many elements, through a reflective and retrospective account of their laboratory experience. I also set out to evaluate their level of understanding. Chief to the inquiry is the extent to which their view of science is sophisticated. Arguably, this topic is concerned with issues intrinsic

to teaching and learning in chemistry (and science at large). In their work on the practice of chemistry education, (Eilks & Hofstein, 2013) maintain:

[Chemistry is] considered by a majority of students as being a subject for only a very few intrinsic motivated students ... and less connected to their life and interests. Since the 1980s, [the focus of] new goals and standards for science curricula ... was no longer the preparation of single students for their career in science and engineering. Most national science education standards worldwide started acknowledging that every future citizen needs a basic understanding of science in general and of chemistry in particular. This re-orientation of the objectives of science education led to intense debate about a potentially promising orientation and structure of the chemistry curriculum to fulfil the newly set goals (p. 2).

This thesis is composed of six chapters. The first chapter explores the problems and issues central to the inquiry. The chief terminologies contained in the title of the thesis will be defined and research questions will be formulated. In the second chapter, I will present a comprehensive review of literature. It will be divided into two distinctive areas of research, one concerning laboratory education and the other pertaining to the nature of science. For both areas, I will deliberate whether to espouse a certain pedagogical and philosophical standpoint and provide a juxtaposition with alternatives, whenever relevant and necessary. Operational definition and exemplification of key terms will be elaborated further. This chapter also summarises (systematic) reviews of research development in pre-laboratory and the nature of science that have been published as a part of this PhD.

In the third chapter, I will explicate the methodological considerations that drive the inquiry. The research paradigm and methodology will be justified, and compared to available alternatives. I will also address ethical issues as well as research validity and reliability. A description of reflective practice espoused in this research will also be a part of this chapter. Research instruments will be described, and data collection and analysis will be elaborated.

In the fourth and fifth chapters, I will present results and discussions from the data analysis and interpretation related to the first part of the study, *i.e.* students' learning experience in the laboratory and the second part of the study, *i.e.* the nature of science in the context of the undergraduate chemistry laboratory. In the concluding chapter, I will summarise all findings and propose two sets of curricular guidelines pertaining to pre-laboratory activities and the nature of science in undergraduate chemistry laboratory education.

Chapter One. Problematique

1.1. Overview of the Study

This thesis is essentially a culmination of three years of intellectual endeavours centred on students' learning in the context of undergraduate chemistry laboratory. It is a record of research findings, systematic reviews of research, pedagogical frameworks, and dialogues on some of the least discussed philosophical discourse in the practice of chemistry education. Substantially, it is an educational research project in the context of undergraduate chemistry education. A host of different research traditions, including history, sociology, and philosophy of science, as well as cognitive psychology illuminate the deliberation of theoretical and methodological frameworks. In an attempt to reach a cohesive and coherent academic research, a certain degree of interdisciplinarity is sought.

Since the beginning of the project in September 2016, there have been substantial changes pertaining to the foci of the research. Initially, the focus was on learning analytics in the context of laboratory education. A careful study on the development of this new field of research was conducted, from around 2010 when learning analytics research emerged up to 2016. Although the number of peer-reviewed scholarly publications in this area was growing, it was soon realised that it still lacked a strong theoretical foundation and robust methodological repertoire. The idea of relying solely on web analytics to elucidate how students learn in the laboratory was considered, at best, incomplete. There was, of course, a merit of importance and relevance, especially in the age where education is increasingly becoming digitised and data science permeates ever slightly more corners of educational practice. But the degree to which learning analytics alone could provide a rich description of learning domains in a context such as the chemistry laboratory was arguably very limited and perhaps too simplistic a view for such a complex learning environment.

Therefore, in the course of the following months, the focus shifted towards an investigation of students' actual learning experience in the laboratory and an attempt at modifying the existing pre-laboratory activities. The notion of nature of science

was then somewhat peripheral. In the second year, it became clear that students' learning attributable to pre-laboratory work was indeed the main focus of the study. It was also palpable that the nature of science has become a second, equally important focus of this study. It was considered so important that a major review of research had to be conducted, which led to a publication on its own. From a methodological perspective, some changes have also been made. This study has developed from originally an educational design research into a phenomenological study. The change in methodology was inarguably fit for purpose, considering the change in foci.

From a personal perspective, the nature of science is a topic that has intrigued me since I was in secondary school. My first encounter with Darwin's "The Origin of Species" at the age of 13 and my struggle with the cognitive dissonance arising from conflicting religious values have rendered this topic a lifelong interest. Likewise, my own experience with laboratory education during my bachelor's degree also had me reflect on the status quo of undergraduate chemistry education. Throughout my career in education, at virtually all levels from kindergarten up to tertiary level, in my capacity as both a researcher and a practitioner, some of the quandaries related to the nature of science have been close to and relevant for my praxis. Accordingly, the absence of dialogue between pedagogy and philosophy in the practice of university science education has primarily motivated me to introduce this topic, in order to lay a foundation for science education research and practice in this context, in which science is regarded not merely as a corpus of knowledge but also a way of thinking, a human endeavour, and an idiosyncratic process.

1.2. Purpose of the Study

Since its inception, this study has always been geared towards practice. Indeed, the very rationale for this research undertaking was mainly problems identified, experienced, and reported in the practice of chemistry laboratory education. This study has at least two purposes, one being a reassertion of pedagogical underpinnings of learning, instructions, and assessments in the laboratory, the other being an argumentation for philosophical validation of undergraduate laboratory curricula. The first purpose has been served by many scholars and researchers in the

field of chemistry and science education, to different extents and on various educational levels. This study is mainly interested in how pre-laboratory activities permeate students' learning as they navigate through concepts, skills, and affective bearings. The second purpose is much less explored in both research and practice, at least as far as undergraduate chemistry laboratory is concerned. Hence, the decision to put a relatively equal weighing on these two foci.

1.3. Research Issues

Essentially, this study is a response to prevailing issues in the undergraduate chemistry laboratory that have been experienced by students and identified by instructors. Students' learning experience is the very central issue in question here. A survey of students' satisfaction was a legitimate point of departure from which this research project was proposed. In particular, disenchantment expressed by undergraduate chemistry students with regards to learning experience in teaching laboratories. Traditionally, these are premises devoted to scheduled laboratory activities as a part of their practical scientific trainings.

Building on previous works on flipped teaching and learning, the role of prior knowledge in the acquisition of new information, and multiple volumes on cognitive load theory, this study is directed towards informing practice by substantiating students' *meaningful* learning experience, whereby their cognitive, affective, and psychomotor dimensions are taken into account. The concept of meaningful learning and its related issues are considered highly relevant to this study, as time and again, literature shows that science educational practice in general puts too much emphasis on cognitive domain (*e.g.*, Eilks & Hofstein, 2013; Ferris, 2010; Kuboja & Ngussa, 2015). In the context of laboratory education, skill-related psychomotor (or conative) domain is almost self-evident, but it is the affective dimension of learning that is often dismissed. This study strives to shed some light on this issue.

Another dimension of science teaching and learning that is often overlooked is the epistemic dimension, which is ironic, because at the very foundation of science lies epistemology: the theory of knowledge. The complexity of learning in the laboratory complicates this issue even more, as careful curricular decisions have to be made in such fashion that if the epistemic dimension is to be addressed in

undergraduate laboratory education practice, it does not jeopardise the already loaded curricular demands experienced by both students and instructors. The crux entailing pedagogy and philosophy is perhaps not an educational issue that lends itself to a simple solution, but it nevertheless exists. This study is an attempt to resolve some of these rarely discussed problems, which will be elaborated in the following subsections.

1.3.1. Learning in the Chemistry Laboratory

The conundrums of learning in the chemistry laboratory have been investigated and reported in the literature. In general, these problems pertain mainly to cognitive domain, whereby students are expected to make optimal use of their mental skills to acquire new knowledge. Having reviewed relevant literature in university laboratory education, Kirschner and Meester (1988) found that laboratory work provided poor learning outcomes in proportion to the amount of time and effort invested by staff and students. They also found that experiments were either overwhelming or trivial. The former was caused by the abundance of information and expected level of problem solving beyond students' comprehension, whereas the latter was a consequence of exercises aimed at verifying concepts already known to student. Both were found to be detrimental to learning and motivation. These findings mirror other reviews such as those of Novak (1988) and Hofstein and Lunetta (1982).

In more recent reviews, the quandaries associated with learning in the chemistry laboratory were differentiated based on the types of laboratory in which learning was expected to take place. For example, Johnstone and Al-Shuaili (2001) contextualise these problems in the framework of Domin's (1999) typology of expository, discovery, inquiry, and problem-based laboratories. Most commonly used in science curriculum, the expository laboratory has been criticised for placing little emphasis on thinking, by instructing students to follow specific procedures to collect data in an uncritical, unengaging manner. Although the inquiry laboratory is often lauded as student-centred and, ergo, giving them ownership of the laboratory activity, inquiry-based instruction could also be criticised for 'placing too much emphasis on the scientific process and not enough on science content' (Domin, 1999, p. 47). They argue further that real open inquiry can only be accomplished after

relevant scientific knowledge and practical methods have been acquired. Therefore, a strategic and well-structured combination of both expository and inquiry laboratory curricula might be the most effective pedagogical approach (See for example, Green, Elliott, & Cummins, 2004). The most recent publications by Seery's research group (Seery, Agustian, & Zhang, 2018a; Seery *et al.*, 2018b) are particularly relevant as this very combination of expository and inquiry laboratory curricula is argued and implemented in practice. This research is an attempt to substantiate some of these arguments.

The chemistry laboratory is also a highly relevant and contextual premise to learn about two structural domains of chemistry, *i.e.* substantive and syntactical structures (Schwab, 1967). Substantive structure of chemistry refers to the conceptual structure pertaining to the discipline that determines the various aspects of inquiry, including the theoretically-motivated interpretation of the results of inquiry. As such, it entails strengths and limitations of the knowledge associated with chemistry. Syntactical structure of chemistry refers to the manner in and the extent to which chemistry as a discipline can verify the knowledge it pursues and produces. It concerns the processes of science inherent to chemistry, from raw data to conclusion. In his work on laboratory education, Kirschner argues that the laboratory is a place where students mainly learn about the syntactical structure of science, through practical work pertaining to *learning to do* science, as opposed to *doing* science like professional scientists do (Kirschner, 1992; Kirschner & Meester, 1988). But because in general students are not fully trained to do science, and because most laboratory curricula are directed towards solely verifying concepts, he argues that the laboratory is not suitable for learning about substantive structure of science. However, more recent works such as those published by Hodson (1998), Domin (2007), Hofstein & Mamlok-Naaman (2007), de Korver & Towns (2015), Teo *e.a.* (2014b), and Bretz (2019) assert the role of laboratory in illustrating key chemical concepts and deepening students' theoretical understanding. The extent to which it serves these ideals depends on various factors, including the laboratory curricula and corresponding instructional designs, but research demonstrates that some insight into the substantive structure of chemistry could be gained through laboratory work.

1.3.2. Pre-laboratory Activities

Many of the problems of learning in the chemistry laboratory are attributed to the overwhelming cognitive demand imposed on students during their laboratory period, as previously argued. One way of addressing these issues is the integration of pre-laboratory activities into the laboratory instruction. Research in the area of pre-laboratory is growing and empirical evidence in support of its implementation also confirms that it indeed facilitates students' learning (Agustian & Seery, 2017; Peteroy-Kelly, 2010). The prevailing issue here is the extent to which pre-laboratory activities actually do what they purport to do.

Previous works delineated several issues pertaining to pre-laboratory activities that need resolving. Winberg and Berg (2007) found that pre-laboratory exercises aimed at assisting students to integrate their theoretical content knowledge into schemata in their long term memory allowed some room for reflection. This was observed as students asked more theoretical and conceptual questions during their laboratory period. However, it is still unclear how they actually manage the influx of new information whilst performing experiments and collecting data, in relation to the corresponding pre-laboratory activities. Similarly, Nadelson *et al.* (2015) substantiated evidence for enhanced student efficacy and efficiency in the laboratory, but the extent to which pre-laboratory videos could be used in support of learning, not only performative tasks, is still unknown. In a slightly different context, van de Heyde and Siebrits (2019) argue for blended learning to manage the flow of information between instructors, students, and the increasingly digitalised platform on which pre-laboratory exercises are made available. They, too, call for more research and iterative evaluation of pre-laboratory exercises geared towards helping students to better prepare for laboratory sessions.

Issues concerning perceived learning goals in the laboratory also belong to the pre-laboratory domain. Galloway and Bretz have investigated some of these aspects, mainly within the framework of meaningful learning in the chemistry laboratory (Galloway & Bretz, 2015a, 2015b, 2016; Galloway, Malakpa, & Bretz, 2016). They have developed and validated an assessment instrument aimed at measuring students' expectation and learning experience related to cognitive and affective

domains of learning in the context of an undergraduate chemistry laboratory course, which is also used in this study. The rationale behind the design of this instrument was the scant evidence for the extent to which meaningful learning actually takes place in the undergraduate chemistry laboratory.

1.3.3. Nature of Science in Laboratory Education

The laboratory has also been used as a context for research on the nature of science (NoS). Several aspects of laboratory education have been investigated, such as the level of scientific inquiry in laboratory manuals (Hegarty, 1978), teachers' epistemological beliefs regarding laboratory activities (Kang & Wallace, 2004), and the impact of laboratory curriculum on students' understanding of NoS (Russell & Weaver, 2011). I have systematically reviewed six decades of research development in the nature of science, from 1963 to 2019 (article submitted, see 7.13). Overall, the laboratory context accounts for around a quarter of published NoS studies, consisting of both pre-college and college levels. This arguably does not do justice to the essential role of the laboratory in science education. Although the role and urgency of the laboratory in pre-college education have been debated elsewhere (Hodson, 1993; Hofstein & Lunetta, 2004; Kirschner, 1992), it is an indispensable element of science undergraduate curriculum (Reid & Shah, 2007).

Lamentably, only 10% of all NoS studies reviewed was conducted in science major undergraduate laboratories. Worse still, only 3% was done in the undergraduate chemistry laboratory. The scant knowledge and intellectual discourse on NoS in the context of science undergraduate laboratory necessitates more investigation as well as contestation. Thankfully, approaches to laboratory education and learning from pedagogy and cognitive psychology have been substantiated. For example, Seery, Agustian, and Zhang (2018) for the chemistry laboratory; Trumper (2003) for the physics laboratory; Wood (2009) for the biology laboratory; and Abdulwahed and Nagy (2009) for the engineering laboratory. I argue that a pedagogical *and* philosophical validation of the undergraduate science curriculum is necessary for meaningful learning in the laboratory. The research development in undergraduate laboratory pedagogies and curricular implementation thereof is satisfactory, but if undergraduate science laboratory education is genuinely aimed at

teaching students about both substantive and syntactical structures of science, philosophical validation of laboratory curriculum is arguably needed.

At a research level, findings from the following example illustrates how both pedagogical and philosophical validation of laboratory curriculum is at work. Schussler *et al.* (2013) found that students' understanding of the creative, tentative, empirical and inferential aspects of NoS as well as the myth of scientific method could be improved, but the combination of pedagogies matters. They argue that expository laboratories paired with explicit, reflective instruction would maximise NoS gains, contrary to national reform recommendations to employ inquiry-based laboratories. These findings require more substantiation and rival approaches, in my view, in order to provide a richer description and a more rigorously-contested discourse on this kind of validation. I would argue that this could potentially lead to a new theory, drawing on salient findings from pedagogy and philosophy of science.

1.4. Problem Statement

The issues identified in the previous section can be summarised in the following problem statement. The undergraduate chemistry laboratory is an educational premise in which students are expected to learn both substantive and syntactical structures of science. This is often concretised and specified in the goals of laboratory courses stated in curriculum documents, such as laboratory and course manuals. The broad categories of these goals include learning about specific technical skills, chemical concepts, cognitive abilities, understanding of the nature of science, attitudes towards science and scientific attitudes (Bates, 1978; Hofstein & Lunetta, 2004). In practice, however, these goals are not always addressed adequately. Discrepancy between the goals stated by laboratory course designers and actual learning goals aspired by students also creates dissatisfaction and, inevitably, disenchantment towards laboratory work. Of all the learning domains pertaining to laboratory education, *i.e.* cognitive, affective, conative (psychomotor), and epistemic domains, the affective and epistemic are often overlooked. Arguably the latter is dismissed altogether, mainly due to an assumption that particularly at science major undergraduate level, an understanding of the nature of science is self-evident (Domin, 2009; Yacoubian & BouJaoude, 2010).

1.5. Definitions

In this section, several key concepts used in the study and encapsulated in the thesis title, *viz.* learning experience, the nature of science, and pedagogical and philosophical validation of curriculum, will be defined in light of the contemporary discourse in science and chemistry laboratory education, philosophy of science, and educational psychology.

1.5.1. Learning Experience

In educational research and practice, students' learning has been conceptualised in various terminologies. Learning outcomes, learning strategies, learning skills, self-regulated learning, are some of the terms associated with students' learning in higher education. In this study, learning is primarily conceptualised as an experience (Marton & Booth, 2013). Learning experience refers to any interaction, course, or exercise in which learning takes place. It includes conventional interactions between students and instructors, and non-conventional ones between students and computer-based resources and online environment. The term is used to underscore the educational goal of the chemistry education, *i.e.* learning, and not necessarily the specific context of undergraduate chemistry laboratory.

The conceptualisation of learning experience in this study draws partially on Vygotsky's theory of learning and development (Vygotsky, 1978). At the core of Vygotskian cognitive theory is the concept of zone of proximal development, whereby the actual development level as determined by independent problem solving is increasingly elevated by means of guidance from instructors or in collaboration with more capable peers, as illustrated in Figure 1. Albeit theorised in the 1970s, it is still widely held as a useful framework for various pedagogical approaches in educational research and practice. By his Russian followers, this theory was later elaborated into a so-called neo-Vygotskian theory, which emphasises the context-embeddedness of learning (Karpov, 2005; van Oers, 2011).

The widespread use of the term learning experience by educational researcher and practitioner alike reflects a pedagogical shift in the design and delivery of education to students. It could be argued that it represents an attempt to update

conceptions of how, when, and where learning takes place. The ubiquity of new educational technologies and digitally savvy students have diversified the ways in which students can learn from and interact with instructors. They become both independent and interdependent learners, who swiftly navigate between resources.

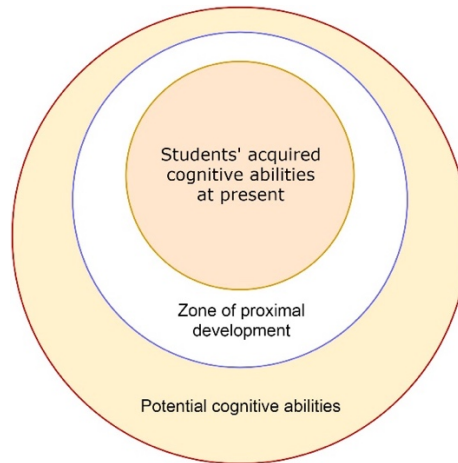


Figure 1. Zone of proximal development (after Vygotsky, 1978)

1.5.2. Nature of Science

The terminology 'nature of science' typically refers to the epistemological commitments underlying the activities of science, *i.e.* science as a way of knowing, or the values and beliefs inherent to the development of scientific knowledge. It also entails an understanding and appreciation of the work of scientists, processes of science, and sociology of science. As a concept, it has been in a discourse of science education for well over a century. Ernst Mach (1838–1916), an Austrian philosopher, physicist, and science educator, is believed to be the first to promote an understanding of what we now describe as the nature of science (Matthews, 1994). Mach upheld the view that scientific theory is an intellectual construction for economising thought and therefore it can only be understood if its historical development is understood.

The decades from 1950 to 1980 represent a period of paradigm shift and conceptual changes in thinking about the nature of science and science education (e.g., Brodbeck, 1961; Cooley & Klopfer, 1961; Kuhn, 1962; Rowe, 1978; Schutz, 1967; Taber, 2017; Welch & Pella, 1967). Novel insights in philosophy of science, new findings from cognitive psychology and pedagogy contributed to a questioning and

rejection of accepted views, for instance, logical positivism in philosophy and behaviourism in the learning sciences.

As an area of research, the nature of science (NoS) encompasses the field of epistemology, a branch of philosophy that is concerned with how knowledge is generated and how it shapes the character of science. In its development, scholars and researchers in this interdisciplinary field come from a diverse background. Among philosophers, NoS debate has traditionally revolved around investigations of the epistemological, methodological, and ontological commitments of science. Nevertheless, there are illuminating, non-philosophical studies of science, such as those conducted by historians, cognitive psychologists, sociologists, economists, anthropologists, and numerous other disciplines (Khine, 2012).

NoS is a fertile hybrid area that blends aspects of various social studies of science. Taber (2017) refers to this interdisciplinary research as Science Studies. Currently, the corpus of knowledge in NoS provides a rich description of what science is, how it works, why it is important to be scientifically literate, how scientists operate as a social group and an enterprise, and how society itself both directs and reacts to scientific endeavours. Akin to scientific knowledge itself, conceptions of NoS are tentative and dynamic: they have changed (and continue to change) throughout the intellectual debate and development of scientific nature, workings, and its societal impact (Duschl & Grandy, 2013). Even until today, it is still contestable whether science, particularly in an educational context, should be conceptualised in cognitive and technological terms or more epistemic and philosophical. However, Niaz (2016) claims that despite the complexity of multifaceted NoS issues and the controversy among philosophers of science themselves, a certain degree of consensus has been achieved within the science education community.

1.5.3. Pedagogical and Philosophical Validation

The notion of ‘pedagogical and philosophical validation’ in this research mainly refers to Hodson’s critiques of science education (Hodson, 1985, 1988, 1993, 1996a, 1996b, 1998). In essence, it can be defined as a process of validating a curriculum by carefully examining relevant pedagogical frameworks that may facilitate the transposition of theory into practice, and by critically engaging with the philosophical

debates and discourse that underlie the conceptualisation of core ideas in the curriculum or, substantive structures inherent to the curriculum at hand.

In the context of undergraduate chemistry laboratory education, his arguments translate into the following. Modern chemistry laboratory courses fail to fully achieve some of their declared goals in relation to students' understanding of science due to:

- instructors' (in this case, including laboratory teaching assistants and demonstrators) own inadequate views about the nature of science; and
- a degree of confusion in the philosophical stance implicit in the corresponding laboratory curriculum.

According to Hodson, the assumption that an assortment of educational outcomes can be served by a single type of learning experience is naïve at best. In order to design a chemistry curriculum that is pedagogically as well as philosophically sound, various goals of chemistry education must be delineated more carefully. As an illustration, different kinds of laboratory experiences may be required for each of the following:

- acquisition of factual and theoretical knowledge;
- substantiation of arguments for and against particular theories;
- practice in using theories for explaining phenomena;
- acquisition of laboratory skills and techniques;
- designing experiments to test hypotheses or to illustrate theories;
- appreciation of socio-economic and historical aspects of science; and
- appreciation of the nature of science, scientific methods and practice.

The attainment of philosophical validity depends crucially on science curriculum designers addressing a number of fundamental questions. Should the major emphasis be scientific knowledge or scientific method? What are the methods of science? What are the role and status of scientific theories? How are they different from scientific laws? How is scientific knowledge validated and disseminated by the scientific community?

1.5.4. Undergraduate Chemistry Laboratory

Although it may seem self-evident to a researcher or practitioner of higher science education, the operational definition of undergraduate chemistry laboratory

has to be established in the context of this study. The undergraduate chemistry laboratory used as a research setting here refers to the teaching laboratory, as opposed to the research laboratory where final year undergraduate students usually conduct their final year research. It is an educational premise where students perform course-related, laboratory-based tasks such as experiments, observations, and computational modelling. This study was conducted in the upper-division physical chemistry teaching laboratory, but it transfers well to other teaching laboratories (organic, inorganic, general chemistry, and so forth). Arguably it is also transferrable to other laboratory-based undergraduate courses in scientific disciplines such as physics and biology. Essentially, this study also draws on research findings and theories from other scientific disciplines.

1.6. Research Questions

The investigation into the research issues stated previously was guided by two main research questions, concerning students' learning experience and their views of science, respectively. Each question was then specified into sub-questions, to refine the various aspects of the issues being addressed.

1.6.1. Question 1

The first main research question is "What are characteristics of students' meaningful learning experience in the undergraduate chemistry laboratory in relation to the pre-laboratory activities?" The rationale for this question is the importance of characterising the learning experience that typifies the chemistry laboratory at undergraduate level. Accordingly, the specification of *meaningful* learning in this study is an attempt to address each learning domain (cognitive, affective, conative, and epistemic domain), and discern connections and interdependence between them. As argued in section 1.3, the issues related to pre-laboratory activities account for a substantial part of this study and there is an evident gap of knowledge in this area.

1.6.1.1. Sub-question 1a. "What are ways in which students prepare for their laboratory work?"

The rationale for this sub-question is that preparation for laboratory exercises could vary among students. In their effort to make the most out of their laboratory learning experience, students are expected to do some preparatory work using a host of resources and activities available to them prior to the start of a laboratory session. Students are at liberty to access these resources at their discretion, any time they want. This sub-question addresses the multifarious modes of preparatory learning in light of the experiment to be conducted.

1.6.1.4. Sub-question 1b. “Which learning goals pertinent to the laboratory are prioritised by students?”

Formulation of learning goals in the laboratory can usually be found in the curriculum documents. Faculty members teaching related courses also set their own aims and objectives with regards to what they expect of students. This sub-question seeks to discern students’ expectations of learning and what they think is the most important.

1.6.1.2. Sub-question 1c. “How do students manage information during their laboratory work, in relation to the pre-laboratory activities?”

This sub-question aims to elicit students’ accounts of strategies to manage the influx of information during their laboratory work. The role of pre-laboratory activities in this context is also investigated. Information processing in the laboratory has been known to play a vital role in the learning process. Theories drawn from cognitive psychology underpin the formulation of related queries to address this sub-question.

1.6.1.3. Sub-question 1d. “To what extent does students’ learning experience influence their affective domain?”

As previously argued, the affective domain of learning constitutes one of the aspects of laboratory education that is often overlooked. Although there is a modicum of work that addresses this quandary, its contextualisation in the pre-laboratory hasn’t been explored. This sub-question is also relevant for the second part of research on the exploration and evaluation of students’ views of the nature of science.

1.6.2. Question 2

The second main research question this study seeks to investigate is “To what extent do students understand the nature of science in the context of the undergraduate chemistry laboratory?” The main rationale behind this is the palpably scant empirical evidence for NoS evaluation in this particular educational setting. Different from most previous works in this area, this study strives to provide a detailed phenomenological description of students’ level of understanding of each NoS aspect.

1.6.2.1. Sub-question 2a. “What are students’ views of the nature of scientific knowledge?”

In the first half of this study, the focus of inquiry is mainly on students’ learning experience in the laboratory in relation to pre-laboratory activities. The nature of science is initially introduced as a peripheral subject within the inquiry. Therefore, one aspect of NoS is chosen to provide a general impression of students’ views of science in a preliminary investigation into this particular research issue. This sub-question aims to explore an aspect of NoS that is arguably the most accessible to students, *i.e.* the (tentative) nature of scientific knowledge.

1.6.2.2. Sub-question 2b. “To what extent do laboratory instructional features influence students’ views of NoS?”

This sub-question aims to discern a certain degree of pedagogical connection between laboratory instruction and students’ views of NoS. There is no pedagogical intervention involved in this study, and therefore this parameter is meant to be exploratory. A context analysis is conducted on the existing laboratory instruction, activities, and curriculum documents, to provide a background for the development of research instruments to address this specific issue.

1.6.2.3. Sub-question 2c. “What is the level of students’ understanding of the nature of science?”

In this evaluative part of the inquiry, a more detailed and encompassing description of students’ understanding of NoS is investigated, according to certain assessment criteria. Three levels of understanding are aimed to be mapped and elaborated, in order to gauge the extent to which the current laboratory curriculum

(and chemistry undergraduate curriculum in general) inform students about the nature of science. Albeit done in a non-interventionistic study, this evaluation is arguably essential for substantiating the argument for philosophical validation of the laboratory curricula, as this research aims to accomplish.

1.7. Significance of the Study

University chemistry education assumes a certain level of laboratory-related skills and conceptual, scientific understanding. Therefore, teaching laboratories have been an indispensable part of undergraduate curricula. Insofar as learning goal setting is concerned, laboratory education has been geared towards specific practical and instrumental skills, scientific reasoning, creativity and problem solving, and social relationships. To an arguably lesser degree, it is also aimed at catering for students' affective experiences and understanding of the nature of science. However, there has been tension between the rhetoric of goal setting and the reality of students' learning, demonstrated by students' satisfaction surveys related to laboratory experience and substantiated by empirical studies in the past years. Critiques of laboratory education often highlight needs for more balance in terms of curricular emphasis: chemical concepts or technical skills, substantive or syntactical structures of chemistry. The literature in this area is growing, but there are several gaps of knowledge that necessitate further substantiation. This study aims to fill these gaps, by providing thick, detailed description of students' account of learning experience and their views of the nature of science.

1.8. Summary

This chapter presented an overview of the study and delineated a dual purpose of investigation, one addressing students' learning experience in the laboratory and the other evaluating students' understanding of the nature of science. Several prevailing issues in undergraduate chemistry laboratory education were elaborated, to lay a foundation for stating the problem to be resolved in this study. Key terminologies were (re)defined in light of the relevant contemporary discourse. The research questions were specified and their rationale explained. Contribution to the field of scholarship in science and laboratory education was reasserted.

Chapter Two. Literature Review

This chapter explores the many dimensions of the chemistry laboratory, which constitutes the central setting of this research. Following the bifurcated foci of the study, this chapter is divided into two parts: one concerning laboratory education and the other addressing the nature of science. In Part 1, I will begin with a critical literature analysis of the role of the laboratory in chemistry education, followed by proposed frameworks for learning in this context. The next subsection is a reassertion of the role of pre-laboratory activities, their rationale, forms, and assessments. In Part 2, I will present a critical review of and, indeed, argumentation for the nature of science in laboratory education. Herein some pedagogical and philosophical considerations will be weighed against the recent and current trends in science education.

Part 1: Laboratory Education



Figure 2. American students in the chemistry laboratory, Hampton Institute (Johnston, 1899)

Although nowadays the laboratory is often regarded as an indispensable part of science education, it was not until the latter 19th century that individual laboratory work became a common phenomenon in science courses in the United States

(Bradley, 1968). Figure 2 illustrates a group of black and native American students doing individual laboratory work in the chemistry laboratory at Hampton Normal and Agricultural Institute, Virginia (nowadays Hampton University). They were to be trained as teachers, but in the era when African Americans were still haunted by the recently abolished slavery, teacher training was limited to basic practical skills, devoid of any higher order skills such as critical thinking and problem solving skills (Gale, 2005). In the European context, the origin of laboratory education as we know today can also be traced back to the 19th century, when Justus von Liebig became a professor of chemistry at University of Giessen in Germany and founded what we now call individual laboratory work (Oesper, 1927; Pickering, 1993).

To date, science education, particularly at tertiary level, is thriving with both practitioners and researchers taking a closer look at laboratories in order to make the most out of its distinctive qualities and characters. Laboratory courses are offered to students as contrived learning experiences in which they interact with materials (Hofstein & Lunetta, 1982), often in a concerted fashion with lectures and tutorials. Each one of them slightly varies in structures specified by the course designers and instructors, but it most definitely involves a central performance phase *in* the laboratory, aside from phases of planning and preparation, analysis and interpretation. But despite widespread and tacit acceptance of the role of laboratory work in science curricula (Sweeney & Paradis, 2004), its essential value has been put to scrutiny. To name but a few, Hodson (1992) and Kirschner (1992) argue that we need to re-examine the way laboratory education has been assumed, practised, and studied.

In the first part of the review, I will elaborate on the arguments for laboratory education research and practice by examining the role of the laboratory in chemistry education and identifying gaps of knowledge. Learning in the context of the chemistry laboratory will be characterised and two laboratory curricula will be explicated, leading to a proposed pedagogical framework for teaching and learning in the laboratory. Narrowing down, a discussion on pre-laboratory work will lay a foundation for incorporating the previously argued pedagogical framework into chemistry laboratory education. The first part will be concluded with feedback and assessment in the laboratory.

2.1. Arguments for Laboratory Education

The case for laboratory education has to be established for a few compelling reasons. Running a chemistry laboratory is not an easy task. It entails a high cost of facilities, staffing, equipment and supplies. Furthermore, most laboratory work also takes up considerable time on the part of both students and instructors. But why exactly is laboratory education so important? Which ideals are to be strived for? Are they actually accomplished, or even attainable in the first place? The following arguments are presented in an attempt to shed light on these issues.

In her editorial piece on the importance of laboratory courses, Bretz (2019) succinctly reasserts the need for substantiating learning in the undergraduate chemistry laboratory, as chemists seem to continue to ignore the lack of evidence of learning in this context. She contends that chemists require evidence of student learning in the teaching laboratory because higher education is influenced by diverse stockholders who do not necessarily share the same value proposition. Laboratory teaching is a multifaceted enterprise that ideally serves a purpose of teaching specific practical skills, affording students a phenomenal experience, nurturing scientific thinking and intellectual development, providing an opportunity for social relationships, and catering for students' affective needs (Hofstein & Lunetta, 2004; Kirschner, 1992). But most of all, it is an excellent context for engaging in activities that give students an insight into the nature of science, the very core of science education that is ironically often overlooked or, in too many cases, even dismissed.

Reid and Shah (2007) argue that the importance of laboratory in science courses used to lie in the need to prepare students for a career in science after they graduate, be it in industry or research. As students shift their career pursuits elsewhere, however, this goal needs to be revisited. Hands-on and minds-on laboratory activities should arguably be directed towards a wider learning process. DeKorver and Towns (2015) also assert that laboratory courses aimed at deeper learning must be designed accordingly.

In his critique of practical work and academic skills in science education, Kirschner (1992) argues that pedagogical approaches to science education, including chemistry laboratory education, should take into account the difference between

substantive and syntactical structures of science. As defined in section 1.3.1., the former concerns the corpus of knowledge, which is a result of research and development in chemistry, along with the corresponding intellectual discourses and philosophical debates. One may address it as theory, consisting of concepts, ideas, and laws. The latter concerns the way scientists do science, encompassing habits, skills, and methods of scientific inquiry. In thinking about laboratory work, these two structures must be taken into account, as they will define how laboratory takes form in its entirety. As an integral part of laboratory exercises, pre-laboratory work should also adhere to this epistemological foundation.

One of the pressing concerns in chemistry laboratory education research is the aspects of learning around laboratory exercises. Findings from studies in this area show that students often conduct experiments absent-mindedly, without really understanding what they are actually doing (DeKorver & Towns, 2015; Reid & Shah, 2007; Rudd II *et al.*, 2001; Teo, Goh, & Yeo, 2014a; Winberg & Berg, 2007). Much of this problem is attributed to the overwhelming burden on the students' cognition within the limited hours of their laboratory period. With so much information to process and new skills to practise, students are left with little space to think about the underpinning theories and nature of scientific work they are dealing with. Adhering to learning theories proposed by Vygotsky (1978) and Sweller (1994), the focus of research on laboratory learning should therefore be dedicated to the reduction of cognitive load, in order to afford students to connect their prior knowledge to the new information, whilst discussing with their peers on how or why they do what they do during an experiment.

Despite ongoing debates on the efficacy and efficiency of laboratory in science education, several arguments for its purpose are still considerably valid. In the following subsection, I will shed light on these arguments and set forth my critique where necessary.

2.1.1. Role of the Laboratory in Chemistry Education

The role of the laboratory in chemistry education — and science education in general — is argued to be essential and distinctive (Hofstein & Lunetta, 2004). Experimental activities in laboratories have been an indispensable part of chemistry

curriculum in higher education for decades. In the context of the UK, bachelors programmes students should typically complete at least 300 timetabled hours, exclusive of project work (Royal Society of Chemistry, 2017), whereas in the US, certified chemistry graduates must have 400 hours of laboratory experience beyond the introductory chemistry laboratory, which cover at least four of the five traditional chemistry subdisciplines (American Chemical Society, 2015).

The laboratory is a place where students observe first-hand how multifarious concepts in chemistry can be observed on a macro-level whilst getting a sense of how scientists work. Russell and Weaver (2011) hold the view that its purpose should echo the purpose of the lecture, which in this case is to invoke interest in chemistry and motivation to learn more about it, as well as to enhance the understanding of chemical concepts and develop problem solving skills. I will argue later that the affective dimension of laboratory has been frequently lauded but not sufficiently studied. Others, like Hodson (1993), argue that the laboratory should focus more on improving practical skills than learning about scientific concepts. Having studied, compared, and critiqued different chemistry educators' and researchers' positions with regards to laboratory education, I synthesised six distinctive roles of the laboratory in undergraduate chemistry education, as summarised in Table 1. Each of these roles will be elaborated in the following subsections.

Table 1. Role of the laboratory in undergraduate chemistry education

Role	Description
Specific practical skills	Planning and execution, manipulation, observation, investigation, and reporting skills
Scientific reasoning	Ability to recognise problems, understand experimental methods, organise and interpret data, test hypotheses, and make generalisations
Creativity and problem solving	Creativity with experimental designs, revision of methods and enacted procedures, data interpretation, and drawing conclusions
Social relationships	Constructive social relationships, team working, peer teaching, and positive learning environment
Affective domain	Attitudes to science (<i>e.g.</i> interest, confidence, motivation) and scientific attitudes (<i>e.g.</i> open- and critical-mindedness, scepticism, curiosity, intellectual honesty)
Understanding of the nature of science	Empirical and tentative nature of science, role of theories and laws, theory-ladenness and philosophical subjectivity, etc

2.1.1.1. Specific practical skills. Kirschner (1992) argues that because one of the goals of university science education is preparing the students for independent scientific work or the application of scientific methods, laboratory education should be directed towards the specific subskills needed. Some of the skills that are considered relevant and important in such a context are planning and execution skills (Kirschner, 1992), manipulation skills (Bradley, 1968), observation skills, investigation skills, and reporting skills (Hofstein & Lunetta, 1982). Seery *et al.* (2018b) also advocate the application of these skills to unknown situation.

2.1.1.2. Scientific reasoning. Laboratory education is important because it directs students to think scientifically. Hofstein and Lunetta (1982) describe scientific thinking as an ability to recognise problems, understand experimental methods, organise and interpret data, test hypotheses, and make generalisations. The primary concern of science education is the pursuit of knowledge and laboratory should provide an access to knowledge and its relationships (Kirschner, 1992). In order to do this, students must be given opportunities to plan and conduct logical procedures and strategies, demonstrate the implications of scientific theories and laws, ask good questions and question the taken-for-granted.

There is growing evidence that especially inquiry-based laboratory activities could enhance the attainment of scientific reasoning. Newer laboratory curricula, such as inquiry-, problem-, and research-based laboratories, emphasise the development of higher cognitive skills. In these curricula, laboratory work acquires a central role of science learning process, not merely a place for verifying concepts. Undoubtedly, the extent to which these curricula serve their purpose is open to investigation, but knowledge in this area is developing. Examples include Rudd II *et al.* (2001), Hofstein *et al.* (2005), French and Russell (2006), Kelly and Finlayson (2007), Zoller and Pushkin (2007), and Weaver, Russell, and Wink (2008). Most recently, Overton's research group described the Transforming Laboratory Learning, aimed at incorporating context-based, inquiry-based, and problem-based learning into the entire laboratory components of an undergraduate chemistry degree (George-Williams *et al.*, 2018). The findings demonstrated that students found the new experiments designed within the aforementioned pedagogical frameworks more challenging. However, they acknowledged that the contextuality of the

experiments allowed them to design their own experiments, which led to an enhanced affective experience.

2.1.1.3. Creativity and problem solving. In his elaborate work on creativity, Weisberg (2006, p. 19) illustrates creativity in science with the discovery of the double helix structure of DNA:

More than simple observation is involved in scientific research. Scientists often draw conclusions from very indirect evidence, so their knowledge and comprehension are critical to their success. This is a step away from the notion of science as the simple discovery and study of objective facts. One could say that the helical shape of the DNA molecule was not an objective fact, in the sense that it was not sitting there to be observed. One might go even further and say that it was a “created fact”.

Laboratory work provides possible avenues for students to be creative with experimental designs, revision of methods and enacted procedures, data interpretation, and even drawing conclusions. When done properly, it gives opportunities for combining ideas, techniques, or approaches in a new way. More open-ended laboratory activities such as those mentioned in the previous argument might be a great context to develop creative thinking (Hofstein & Lunetta, 1982).

Laboratory work is also a relevant context for learning to apply an academic approach to a problem, in the form of an investigation. Kirschner (1992) argues that university science students are essentially scientists in training, so they have to familiarise themselves with the way scientists carefully examine a situation and acknowledge that there is actually a problem, define the problem to be solved, specify the most suitable strategy, solve the actual problem, and evaluate the results to see if the problem has been solved. In the science laboratory, students can develop competence in solving a problem (Galloway *et al.*, 2016). With that in mind, Kirschner proposes a model for academic problem solving as shown in Figure 3.

2.1.1.4. Social relationships. The laboratory is not only a place for conducting scientific experiments, it also provides an opportunity for social interaction, in which discussions are encouraged (French & Russell, 2006). Therefore, it has a potential to enhance constructive social relationships defined by factors such as cohesiveness, task orientation, goal direction, and democracy (Hofstein, Nahum, & Shore, 2001). Hofstein and colleagues argue that much of this potential is attributed to the less

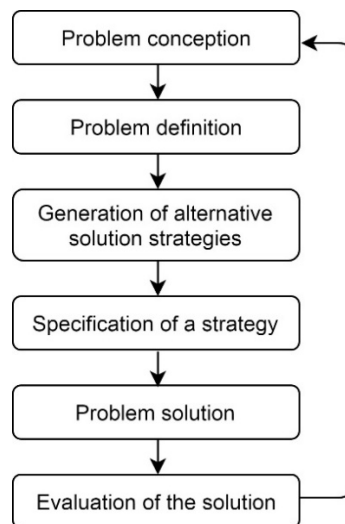


Figure 3. Model for academic problem solving (Kirschner, 1992)

formal nature of social interaction in the laboratory as opposed to, for example, a lecture situation. It also promotes team working (Edward, 2002), peer teaching (Seery *et al.*, 2018a), and a positive learning environment (Tsai, 1999).

2.1.1.5. Affective domain. According to Johnstone and Al-Shuaili (2001), affective aims in science laboratory can be divided into two main categories: attitudes to science and scientific attitudes. The former constitutes general affective aspects such as confidence, motivation, interest, enjoyment, and satisfaction. The latter refers to traits and ways of thinking pertinent to science, such as open- and critical-mindedness, scepticism, curiosity (Zion & Sadeh, 2007), and intellectual honesty (Aiken Jr & Aiken, 1969).

Albeit often stated in curriculum goals, the affective dimension of laboratory education is not much researched (Agustian & Seery, 2017; Galloway *et al.*, 2016). In their second elaborate review on laboratory education, Hofstein and Lunetta (2004, p. 34) assert the following:

The failure to examine effects of various ... science experiences on students' attitudes is unfortunate since experiences that promote positive attitudes could have very beneficial effects on interest and learning. The failure to gather such data is especially unfortunate in a time when many are expressing increasing concerns about the need for empowerment of women and underrepresented minority people in pure and applied science fields.

This is arguably an even more compelling case for addressing the affective dimension of science education in the present time, where attitudes towards science and scientific attitudes ironically decline whilst access to scientific information is wider

than ever before. Edward (2002), for example, found that published analyses of laboratory activities indicate low motivation among participants, with students finding chemistry irrelevant and boring. This, in turn, makes us 'swing away from science' (Osborne, Simon, & Collins, 2003, p. 1050). On the bright side, Wong and Fraser (1995) found that chemistry laboratory classes which display favourable levels of learning environment factors such as student cohesiveness and open-endedness promote student enjoyment of their chemistry lessons.

2.1.1.6. Understanding of the nature of science. As mentioned previously, the role of laboratory education that addresses the nature of science is often overlooked and even worse, dismissed. In a critical review of six decades of research development in the nature of science in science and laboratory education (Agustian, 2019), I found that only about one fifth of the scholarly literature in nature of science addresses the laboratory as a setting of investigation and intervention. This raises even more concern considering there is still lack of attention to the nature of science in both research and practice, whilst it is often lauded as a goal of science education (Abd-El-Khalick & Lederman, 2000; Goff *et al.*, 2012; Marchlewicz & Wink, 2011; Martin-Dunlop, 2013; Ross, Hooten, & Cohen, 2013). I will argue further about this aspect later in this chapter (See sections 2.7 and 2.9).

2.2. Student Learning in the Chemistry Laboratory

The laboratory is a complex facility in which various instruments, chemicals, and people are intertwined in multifarious scientific and educational endeavours. For novice students, the level of complexity can be daunting as they have to deal with new information, instructions, materials, and equipment, whilst recalling theory and prior knowledge, in order to acquire new skills and knowledge. The challenge of learning in such a complex environment has much to do with the amount of cognitive load students have to manage in a particular laboratory session. In designing an educational intervention aimed at enhancing learning experience in the laboratory, this should therefore be taken into account.

In the literature, several approaches to teaching and learning in the laboratory have been characterised. According to Russell and Weaver (2011), the traditional verification laboratory is the oldest and most well-established approach to teaching

and learning in the laboratory. Domin (1999) elaborates the typology of laboratory instruction, and the corresponding student learning, into expository, discovery, inquiry-based, and problem-based laboratories. He bases his classification on the outcomes of laboratory work (either predetermined or undetermined), approaches to reasoning (either deductive or inductive), and experimental procedures (either given or student-generated), as shown in Table 2.

Table 2. Descriptors of laboratory instruction styles (Domin, 1999)

Instruction styles	Descriptors		
	Outcomes	Approaches	Procedures
Expository	Predetermined	Deductive	Given
Discovery	Predetermined	Inductive	Given
Inquiry-based	Undetermined	Inductive	Student-generated
Problem-based	Predetermined	Deductive	Student-generated

According to the Schwab–Herron framework, laboratories can be arranged on a continuum from verification (level 0) to authentic inquiry (level 3), depending on whether the teacher or the student directs most of the activities (Schussler *et al.*, 2013). A particular laboratory instruction style often develops into an entire laboratory curriculum, for instance, Course-based Undergraduate Research Experiences (CURE), developed by the Center for Authentic Science Practice in Education (Chase *et al.*, 2017). This laboratory curriculum evolves from the inquiry-based instruction style, aimed to introduce students to research activities in a cost-effective manner. In the following subsection, I will elaborate on and critique two of these laboratory curricula.

2.2.1. Traditional Laboratory Curriculum

The traditional expository laboratory curriculum has been designed and implemented for well over a hundred years (NRC, 2006) so that laboratory activities can be performed simultaneously by a large number of students at a low cost. Domin (1999) argues that this curriculum was developed in order to minimise resources in terms of staff, space, time, and equipment. In this laboratory, students perform tasks described in the manual, observe and interpret phenomena, and report their observation. They verify scientific phenomena deductively through a given procedure and goals described in the manuals or outlined earlier in the textbook or lectures. It

is by nature confirmatory (Russell & Weaver, 2011).

Hofstein and Lunetta (2004) concede that the predominant “cookbook” feature of this laboratory gives virtually no attention to the planning of investigation or results interpretation. Experiments are regarded as foolproof efforts where the right answer is certain to emerge for every student if the predetermined procedures are followed (Kirschner, 1992). This laboratory curriculum has been criticised as placing very little emphasis on scientific thinking, being an ineffective means of conceptual change, leading to virtually no meaningful learning, and being unrealistic in its portrayal of scientific experimentation (Domin, 1999; French & Russell, 2006; Kirschner, 1992; Russell & Weaver, 2011).

2.2.2. Inquiry-based Laboratory Curriculum

The inquiry-based laboratory curriculum is designed to address the issues associated with expository experiments (George-Williams *et al.*, 2018). Compared to the traditional expository curriculum, the inquiry-based curriculum puts more focus on the student than on the manual and instructions during the laboratory (Russell & Weaver, 2011).

When properly developed, Hofstein *et al.* (2001) argue that inquiry-based laboratories have the potential to enhance students’ constructive learning and conceptual understanding, particularly when conducted in the context of the conceptual development of the topic taught (Russell & Weaver, 2011). There is a rather extensive body of literature in inquiry-based learning in general education, and the part where this approach is adopted in a laboratory setting appears to deliver its promises. See for example, Barnea, Dory, and Hofstein (2010), Hall and Vardar-Ulu (2013), Hofstein *et al.* (2001) Kanter *et al.* (2003), NRC (2006); Hofstein *et al.* (2001), and Weaver *et al.* (2008). However, this curriculum is not without shortcomings, and the studies that have claimed its success are not without flaws. In Domin’s (1999, p. 546) words:

The amount of credence one places on these findings is reserved for the reader. In no case did the authors perform a controlled study, or state how the assessment was made, or offer empirical evidence—other than student self-reports— to support their conclusion.

Domin holds the view that the inquiry activities assumed formal operational

thought rather than attempting to develop it, by requiring students to simultaneously attend to new subject matter concepts, unfamiliar laboratory equipment, and novel problem-solving tasks, and therefore placing too much demand on the learner's working memory. Kirschner, Sweller, and Clark (2006) have reviewed and compared studies on guided and unguided instruction in education, making a reference to constructivist, discovery, problem-based, experiential, and inquiry-based teaching of novice and intermediate learners. They came to a conclusion that the body of research is not strong enough to support the claim. Unguided instruction is less effective and there is also evidence that 'it may have negative results when students acquire misconceptions or incomplete or disorganised knowledge' (p. 84).

2.3. Pedagogical Frameworks for Learning in the Laboratory

Aside from design and development of tools and methods, several pedagogical approaches have also been proposed in the literature of laboratory education. A sound pedagogical approach is crucial in laboratory education and science education at large. Kirschner (1992) warns scientists who also teach to be cautious of the function of laboratory experiments in an educational setting. In professional science, where scientists conduct their research enterprise, experiments are deployed in favour of theory development. In educational science, on the other hand, experiments serve a range of pedagogical functions. It is therefore very important that the whole laboratory course is designed within an appropriate pedagogical framework. Course designers must have adequate knowledge and expertise in educational and curriculum development theories. In general, laboratory course designers should strive to:

... implement the principles of ... differentiation and integra[tion] ... by bridging the gap between what the learner already knows and what he needs to know [in order] to learn and retain new instructional material efficaciously (Ausubel, 2000, p. 148).

The well-established research in educational and empirical psychology provides a useful platform on which to design and develop an effective laboratory curriculum. There are at least three distinctive research traditions that shape the development of learning theories, *i.e.* behaviourism, cognitivism, and constructivism. The first research domain was founded back in the early 20th century, when John Watson published his seminal article on a behaviourist view of psychology (Watson, 1913).

Although his theory partly developed into an educational theory, it has been criticised as offering only limited explanations with regards to learning (e.g., Brady, 1996; Goddard, 1997; Novak, 1988). Modern educational research, including in chemistry education research, is mostly underpinned by cognitivism and/or constructivism (e.g., Goedhart, 2015; Seery, 2015), which is also the case in this PhD research.

This study was conducted within a framework for supporting learning in a complex environment by adopting the cognitive load theory, which is well investigated by Johnstone and colleagues (2000, 2006; 2001; 1994; 1998; 1999), Sweller and colleagues (1994; 2011; 1991), and Kirschner and van Merriënboer (1992; 2006; 2017; 2003; 2005). It also drew on theoretical framework from constructivism, mainly from the works of Novak (1997, 2005; 1988; 1993, 2004) on learning science and the science of learning, and Hodson (1985, 1988, 1992, 1993, 1996a) on science and laboratory pedagogies from philosophical viewpoint. The following subsections will elaborate on the theoretical frameworks adopted and contextualised in this research.

2.3.1. Cognitive Load Theory

Drawing on similarities to theory of evolution by natural selection, cognitive load theory puts an emphasis on human cognitive architecture, which is based on the distinction between working and long-term memory. In terms of capacity and duration, working memory is finite, which means that a large number of information interactivity will impose an overload on working memory, unless they are incorporated in the established knowledge structures (*i.e.* schemas/schemata) held in long-term memory. According to Sweller *et al.* (2011), the purpose of instruction is to increase the capacity of knowledge stored in the long-term memory. If nothing has changed in the long-term memory, nothing has been learnt.

The theorists classify cognitive load into three categories, based on the way the cognitive system processes the incoming information.

- If the interacting elements are essential to learning, *intrinsic cognitive load* is at place. In principle, it reflects the difficulty of the materials at hand.
- If they are not directly related to learning but more of a function of a particular procedure used when extracting information out of the materials at hand, they

are classed as imposing *extraneous cognitive load*. Human cognitive system processes both intrinsic and extraneous cognitive loads in an identical fashion.

- Germane cognitive load refers to the extent to which working memory is dealing with the cognitive system. If the working memory is dealing largely with elements intrinsic to the task, germane cognitive load is high. If it is dealing with elements extraneous to the task at hand, germane cognitive load is low.

According to Moreno (2010), the cognitive load theory has been inspiring experimental studies aimed at evaluating instructional designs for about three decades, but its conceptual, methodological, and practical limitations have also been identified. For example, the inclusion of intrinsic cognitive load has been seen as conceptually problematic, because mental load as defined by intrinsic cognitive load cannot arise before a learner has engaged in a learning task. It is beyond the scope of this thesis to elaborate the critique of this theory further. However, those limitations are taken into account.

The implication of the cognitive load theory for laboratory learning is high. Johnstone *et al.* (1994) proposed a model that represents learning processes associated with laboratory works (Figure 4). The model depicts how students interpret, rearrange, compare, and prepare information in their working memory while retrieving prior knowledge, skills, and experiences from their long term memory. They argue that learning is considered successful when a significant amount of information is stored in the long term memory and retrievable whenever needed.

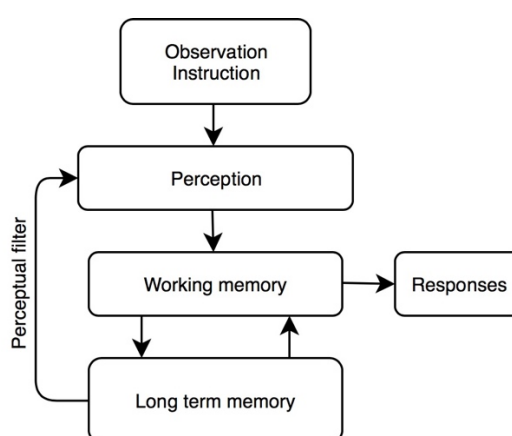


Figure 4. Information processing model in the laboratory (after Johnstone *et al.*, 1994)

In the information processing model, it is argued that seasoned and novice scientists, including those in training, perceive information during laboratory in a

different way. Seasoned scientists know that not all information in the laboratory is relevant or important for them to pay attention to. In contrast, novice scientists are still unable to distinguish the ‘signal’ from the ‘noise’, which is why they often find laboratory an overwhelming experience. This overload of information can be explained by the limited capacity of working memory. Bigenho *et al.* (2013) argue that the objective of any learning endeavour is the acquisition, storage, and retrieval of information in long term memory at any given time. However, since the process of learning requires that information first be interpreted, rearranged, compared, stored and prepared in the working memory, pedagogical approaches aimed at enhancing learning should focus on reducing load on this short term space.

2.3.1.1. Effective learning in the laboratory. The conundrums of learning in the laboratory lie mainly in the fact that improper management of cognitive load often inhibits deep learning, or any learning whatsoever. In cognitive terms, the framework proposed to support learning in this study could be summarised as such: Effective learning takes place when students are able to manage the intrinsic cognitive load, reduce the extraneous cognitive load, and capitalise on germane cognitive load, as visualised in Figure 5. The last part means that in all its complexity of learning environment in the laboratory, students should be able to focus on dealing with elements intrinsic to the task, rather than external (or indeed, extraneous) factors that are not essential for learning.

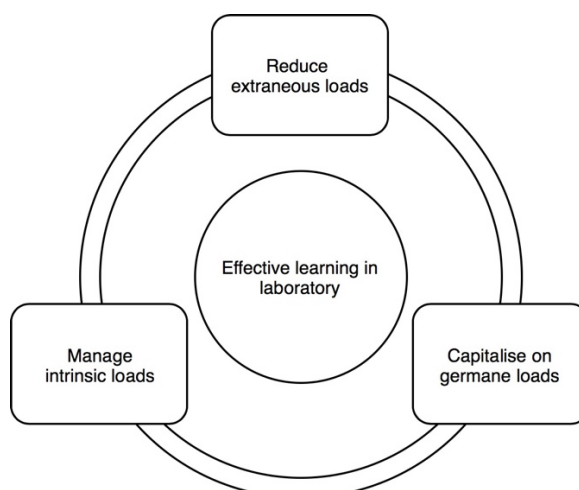


Figure 5. Framework for effective learning in the lab based on cognitive load theory

One way of managing intrinsic load and reducing extraneous load is by providing relevant information prior to a laboratory session. In teaching and lecture,

a similar method known as flipped classroom has been well researched (Ryan & Reid, 2016; Schell & Mazur, 2015; Seery, 2015; Seery & Donnelly, 2012). The principle of this student-centred pedagogy is moving the direct instruction from the group learning space to the individual learning space, often in the form of asynchronous online viewing, so that the synchronous class time can be devoted to more interactive learning exercises such as problem solving and discussion (Schell & Mazur, 2015). The flipped learning pedagogy transfers well to laboratory education. Teo *et al.* (2014b) found that it helped students develop a better understanding of theory underpinning the experiment they conducted in the laboratory. It also reduced their anxiety about complex experimental procedures.

2.3.1.2. Learning in a complex environment. Apart from the cognitive aspects of learning, the affective dimensions of learning need to be addressed adequately, as previously proposed elsewhere (Agustian & Seery, 2017; Seery *et al.*, 2017). The integration of cognitive, affective, and psychomotor dimensions in the laboratory has been known to be key to learning, as found in the work of Galloway and Bretz (2015a). This mode of integrating the aspects of learning is formally conceptualised as complex learning or meaningful learning. Both concepts are used in this thesis.

Van Merriënboer and Kirschner (2017) define complex learning as the integration of knowledge, skills and attitudes by coordinating qualitatively different constituent skills to be transferred to or applied in daily life. According to Van Merriënboer *et al.* (2003), four interrelated components are essential in complex learning, *i.e.* learning tasks, supportive information, just-in-time information, and part-task practice. These components have been elaborated in the context of the undergraduate chemistry laboratory (Agustian & Seery, 2017).

One of the arguments of complex learning is that novices learn complex tasks in a very different way than they do simple tasks. A framework for supporting learning in such complex environment is primarily composed of two elements:

- scaffolding, whereby constituent skills are coordinated from the outset with an emphasis on the overall task's complexity; and
- providing information in advance of a complex learning scenario, for instance by means of pre-laboratory activities.

The latter is a strategy that entails two types of information that need to be integrated in order to complete a task, namely (1) supportive information, which is of general, abstract nature, with high intrinsic complexity; and (2) procedural information, which is of recurrent, consistent nature.

Complex learning is always involved with achieving integrated sets of learning goals. It has little to do with learning separate skills in isolation, but it mainly deals with learning to coordinate and integrate the separate skills that constitute real-life task performance. Ergo, in complex learning the whole is clearly more than the sum of its parts because it also includes the ability to coordinate and integrate those parts (Van Merriënboer, Clark, & De Croock, 2002). In a laboratory situation, this translates into an integration of laboratory skills with the other dimensions of learning argued in the beginning of this chapter, such as scientific reasoning and affective domain.

Professional scientists can effectively perform constituent skills because they have highly complex cognitive schemata available that help them to reason about the domain and to guide their problem solving. Schemata is an organised accumulation of knowledge stored in the long term memory (as visualised previously in Figure 4) that can be retrieved anytime one needs to perform a particular task. It enables use of the same knowledge in a new problem situation because they contain generalised knowledge that can serve as an analogy. Van Merriënboer *et al.* (2002) assert that educational programmes for complex learning should pay attention not only to the coordination and integration of constituent skills, but also to these qualitative differences in desired exit behaviour of constituent skills.

According to Kirschner (1992), students engaged in practical work often get so embroiled in (the details of) what they are doing that they often miss the underlying concept they were supposed to be studying. Apart from getting lost in the details, students often do not have either the theoretical knowledge or the ability to function at the cognitive level (formal operational) that is necessary to see or infer the patterns present in the data which they are collecting.

2.3.2. Human Constructivist Pedagogy

In the decade of 1980s, around the time that Sweller and colleagues developed cognitive load theory, Novak and his research group also developed human

constructivist pedagogy. Essentially, human constructivism is a view of meaning making that encompasses both a theory of learning and an epistemology of knowledge building. It offers a heuristic and predictive power of a psychological model of human learning together with the analytical and explanatory potential embodied in a unique philosophical perspective on conceptual change, as visualised in Figure 6 (Mintzes *et al.*, 2005). This pedagogical framework asserts that individuals construct meanings by forming connections between new concepts and those that are part of an existing framework of prior knowledge.



Figure 6. Concept map of Human Constructivism (after Novak, 1993)

In human constructivist pedagogy, Novak seeks to find unity among the processes of meaningful learning, knowledge restructuring, and conceptual change. He argues that much of good scientific inquiry produces gradual and assimilative learning. This pedagogical framework is relevant for undergraduate chemistry

laboratory education and adopted in this study because it strategically unifies cognitivist and constructivist approaches to learning. While cognitive load theory is primarily focussed on human cognitive architecture, human constructivist pedagogy embeds phenomenological elements into the mechanics of cognitivism. It departs from a rather instrumentalist view of learning and arrives at a more humane perspective. This relevance will also be observed in the methodological rationale for this research.

As an illustration, during a laboratory exercise, a cognitive process called *subsumption* may take place, resulting in a "weak" form of knowledge restructuring and an incremental change in conceptual understanding, as illustrated in Figure 6. The term 'subsumption' refers back to Ausubel's (1963) ideas on cognitivist educational psychology. It models a process of meaningful learning (as opposed to rote learning), whereby new knowledge, composed of more specific, less inclusive concepts, is linked to more general and inclusive concepts that are already a part of the learner's cognitive structure. This process is exemplified by a student learning structural parts of a molecule. In contrast, another process may also take place, namely *superordinate learning*. In such process, new, more general, inclusive, and powerful concepts are acquired that subsume existing ideas in a student's framework of knowledge. This kind of learning often results in a radical, "strong", and significant reordering of cognitive structure and may produce the kind of conceptual change that we typically experience in creative or particularly insightful moments (Mintzes & Wandersee, 2005). It is now clear that this kind of learning is responsible for many of the revolutionary breakthroughs that Kuhn (1962) describes as "paradigm shifts" in revolutionary science. Mintzes & Wandersee describe further that superordinate learning results in strongly hierarchical, dendritic, and cohesive set of interrelated concepts; a conceptual framework. As students progress from mainly expository laboratory curriculum in their first years to more inquiry-based, investigative curriculum in the upper years, it is expected that they also progress within the spectrum of rote learning to meaningful learning. I argue that the ultimate goal of learning in the laboratory should be that of superordinate learning, whereby insightful moments lead to significant knowledge restructuring and ever slightly more interconnected conceptual frameworks.

2.4. Pre-laboratory

As part of my work, I wrote articles for publication in scientific journals. In the literature of laboratory education, there was scant knowledge in the way pre-laboratory work has been researched over the years. A review of four decades of research development in pre-laboratory activities was therefore published on *Chemistry Education Research and Practice* (Agustian & Seery, 2017). This subchapter is essentially a summary of that review.

In general, pre-laboratory is an area of research which is still highly relevant to chemistry education practice. The body of research on pre-laboratory is mainly occupied with various tools and methods to assist students with the preparation for laboratory activities. Dating back to four decades ago, Fine *et al.* (1977) used slides and audiotapes to demonstrate chemical concepts prior to a laboratory session, whereas Kolodny and Bayly (1983) used pre-lab quizzes to help students prepare by ‘forcing’ them to read the laboratory manual. Pre-laboratory tasks which go further than just requiring students to read the manual proved to be useful and, to some extent, effective (Chittleborough, Mocerino, & Treagust, 2007; Gammon & Hutchinson, 2001; Rollnick *et al.*, 2001; Winberg & Berg, 2007). In some context, pre-laboratory work also constituted a short lecture on the experiment by a demonstrator *in* the laboratory, often preceded by a quiz and followed by a discussion (Johnstone *et al.*, 1994; Meester & Maskill, 1995; Smith, 1987).

With the advent of ubiquitous information technology in higher education, the laboratory increasingly becomes digitalised. Weibel (2016) deployed all-electronic formats for obtaining introductory materials, preparing pre-lab reports, recording and analysing data in a simulated electronic lab notebook, and submitting the final report. Platforms such as Google Drive and Google Docs were used to facilitate file sharing and storing. He found that students preferred this entirely online system once they got accustomed to working within the new platform. A significant increase in laboratory grades was also observed. In the same year, O'Sullivan and Harrison (2016) found that computer-based pre-laboratory resources aimed at supporting pre-university students of Chinese origin offer considerable benefits. For those whose first language is not English, the challenges associated with laboratory learning in an

English setting are even bigger. The use of videos of experimental techniques, simulations and glossaries is shown to help them build confidence and cognition.

Additionally, there are some significant findings on the learning outcomes of online-based pre-laboratory. By answering pre-laboratory questions online, students get immediate feedback and avoid the notorious habit of last minute copying of answers from their peers, as they demonstrate improved learning outcomes and better preparedness (Abdulwahed & Nagy, 2011; Gryczka *et al.*, 2016). Both students and demonstrators show positive attitude towards online-based laboratory resources (Kolk *et al.*, 2012; Srisawasdi, 2012), and flexible learning format helps student manage experimental procedures whilst keeping theoretical underpinnings in mind (Gregory & Di Trapani, 2012). While the former demonstrates an affective benefit of online-based laboratory resources, the latter is a sound evidence of cognitive load reduction.

Online pre-laboratory resources also deliver their promises. Hall and Vardar-Ulu (2013) found that the pre-laboratory work in the electronic notebook format they used enabled students to create a platform on which they work out their inquiry, mindfully set experimental goals and hypotheses, and formulate questions about the experiment they were going to do. This in turn allowed students to address any immediate or potential knowledge gaps. Echoing these findings, Fang, Hsu, and Hsu (2016) discovered that by scaffolding the inquiry units, including pre-laboratory section, students exhibited significant learning gains in conceptual knowledge and performed better inquiry abilities regardless of which condition was used.

One of the most promising novel tools in pre-laboratory is the creation of pre-laboratory videos. Gregory and Di Trapani (2012), for example, use pre-lab videos showing how to conduct relevant laboratory procedure within blended learning context that they adopt as a framework. Accordingly, Fung (2015) supplements previously published work of Teo *et al.* (2014b) on flipped teaching by introducing first-person perspective filming technique so as to provide students with a more 'real' experience of doing the experiment prior to a lab session. Both of these examples, however, only deal with aspects of laboratory skills. There is still lack of specifically made videos on theoretical background that are tailored to each experiment.

2.4.1. Rationale for Incorporating Pre-laboratory Activities

It is commonly accepted that students' learning experience in the laboratory is very dependent on how well they have prepared. Students are usually urged to prepare their laboratory session by reading the lab manual, reviewing related concepts from lectures, and becoming familiar with the techniques and manipulations of the experiment, but few students actually do so. Lack of preparation is one of the factors that causes anxiety during the laboratory work (Kolodny & Bayly, 1983).

Anxiety towards the laboratory should be reduced when students know they are adequately prepared before coming to the laboratory session (Starkey & Kieper, 1983). It was clear that if improvement in laboratory learning was to take place, something would have to be done to give the student access to some of the long-term memory stock of the teacher. This led to the introduction of pre-laboratory activities (Johnstone *et al.*, 1994). The aim of the pre-laboratory activities is to prepare students to take an intelligent interest in the experiment by knowing where they were going, why they were going there and how they were going to get there (Johnstone *et al.*, 1998).

Agustian and Seery (2017) have reviewed literature on pre-laboratory in the last five decades. Based on the analysis of the research development in this area, pre-laboratory activities have been used on the ground of at least three rationales, *i.e.* to introduce chemical concepts, to introduce laboratory techniques, and to address affective dimensions. Each rationale is approached by different methods, as shown in Figure 7.

Referring to the literature, there are at least five overarching themes of how and why pre-laboratory has been used. Firstly, it fosters learning of chemical concepts (Gryczka *et al.*, 2016; Kirk & Layman, 1996; Limniou, Papadopoulos, & Whitehead, 2009; Nadelson *et al.*, 2015; Teo *et al.*, 2014b; Whealon, 2016). Secondly,

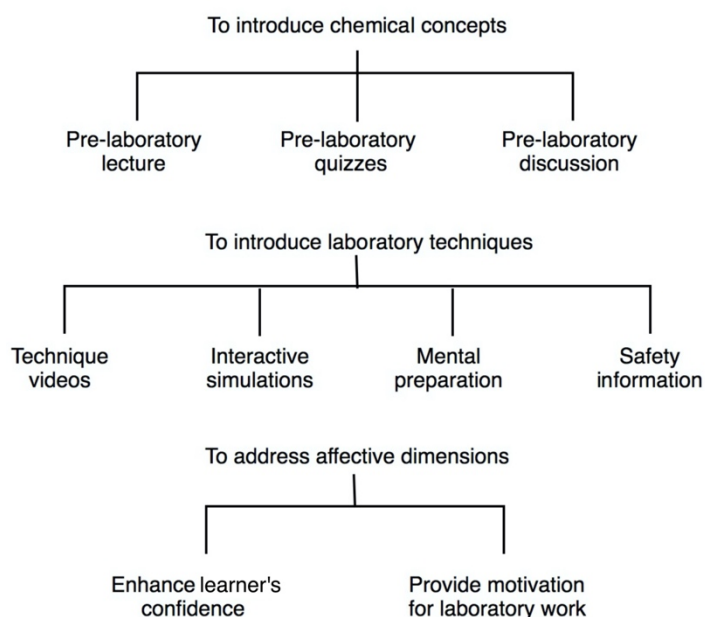


Figure 7. Rationales for and approaches to pre-laboratory activities

it improves laboratory skills and efficiency (Fung, 2015; Lair, 2011; Peteroy-Kelly, 2010; Towns *et al.*, 2015). Thirdly, it raises awareness of safety in laboratory (Abdulwahed & Nagy, 2011; Gregory & Di Trapani, 2012; Meester & Maskill, 1995; Miller, Heideman, & Greenbowe, 2000). Fourthly, it enhances affective experiences in the laboratory (Chittleborough *et al.*, 2007; Donnelly, O'Reilly, & McGarr, 2013; Galloway & Bretz, 2016; Johnstone & Al-Shuaili, 2001; Merritt, Schneider, & Darlington, 1993; O'Sullivan & Harrison, 2016; Supasorn *et al.*, 2008). And lastly, it facilitates post-laboratory aspects such as report writing and corresponding calculations (Kolodny & Bayly, 1983; Limniou *et al.*, 2009; McKelvy, 2000; Nichols, 1999; Vianna *et al.*, 1999). Some of these themes will be elaborated in the following subsections.

2.4.1.1. Understanding of chemical concepts. Pre-laboratory has been used to foster learning of chemical concepts since its early development. Consider, for example, the work of Kolodny and Bayly (1983) on computer-based pre-laboratory quizzes, in which students were required to take a quiz prior to their laboratory practical, as many times as necessary, until they scored 4 out of 5. They argue that the quizzes provide an opportunity to reinforce the concepts needed for laboratory. Similarly,

Isom and Rowsey (1986) also found that unfamiliar abstract chemical concepts were more effectively presented by a pre-laboratory preparation period, which significantly improved the academic performance of students taking general chemistry laboratory.

One of the most pressing concerns in chemistry education at university level, especially in the first year of transition from secondary education, is discontinuity between high school and college chemistry. Zare (2008) argues that while the former is predominated by rote learning and memorisation, the latter demands more reasoning from understood concepts. In the context of laboratory, the understanding of concepts during a practical could be more challenging than in a lecture, as students have to deal with psychomotor aspects of conducting an experiment at the same time. Furthermore, students often had difficulty linking their prior knowledge to the experiments in the lab, suggesting the need for pre-laboratory exercises designed to achieve closer integration between theory and experimentation (Tan, 1990).

Domin (2007) deployed a pre-laboratory activity whereby students were to solve a problem statement one week prior to the laboratory session. During the experiment, students were required to design a viable procedure, assisted by a demonstrator through a Socratic method. Data shows that students were more engaged cognitively while performing a pre-laboratory activity in a problem-based environment.

In their recent study on instructional support on organic chemistry, Box *et al.* (2017) found that well-designed pre-laboratory videos enabled demonstrators to explain concepts more efficiently and, therefore, focus on higher-order thinking. They praised the benefit of explaining chemical concepts through a video, as it provides method of presentation not possible in a lecture, by means of animation within a manageable scope. The videos in their study, which covered technique, instrumentation, and calculation, were created in order to reduce cognitive load during the experiment, so that students can absorb information more effectively. This study also confirms the previous work of Gryczka *et al.* (2016) on electronic pre-laboratory and student engagement, as students think this type of pre-laboratory helps them understand the relevant concepts and improve their performance in the laboratory.

There is, however, a caveat to this rationale for pre-laboratory. Pickering (1987) alerts instructors about imposing a preparation structure with too much theoretical content on students. By forcing theory on them, students' working memories might be overloaded. Kirschner (1992) goes even further by arguing that laboratory courses are not particularly well suited for conveying the substantive structure of scientific knowledge, which constitutes relevant concepts and theories, to novice learners. He is convinced that they are better suited for helping them to become proficient in the syntactical structure of scientific knowledge, which constitutes scientific processes and methods. Even if students do have adequate prior knowledge regarding the principles underpinning the experiment they are about to conduct, it may not guarantee that they will actually use the knowledge effectively (Tan, 1990). Thus, the effectiveness of any prior knowledge will depend critically upon the student's ability to relate the experimental procedures and findings to their prior knowledge. Pickering (1987) contends that the best method has to allow reasonable latitude in terms of modes of preparation and accommodate various learning needs of students. But most importantly, it should get students to optimise their use of working memory by filtering the noise out ahead of time and making proper connection between their prior knowledge and the experiments.

2.4.1.2. Laboratory skills and processes of science. Akin to the previous theme, pre-laboratory has also been used to improve laboratory skills and efficiency. Moore, Smith, and Avner (1980) observed that computer-assisted instruction (CAI) in their pre-laboratory resources facilitated students' performance, particularly when the experiment was less structured. They also found that in a highly structured laboratory, students could basically operate without really understanding what they were doing. However, this typical 'cookbook' approach has been criticised as being an unrealistic representation of laboratory experimentation and leading to low learning outcomes (Johnstone *et al.*, 1994; Merritt *et al.*, 1993). The implementation of pre-laboratory is therefore most efficient when there is a sense of open-endedness and inquiry approach, which will be discussed later.

Manipulative skills in conducting an experiment lie at the heart of laboratory education (Johnstone & Al-Shuaili, 2001). They are what distinguish it from the

chemistry delivered through lectures. But they are by no means the only practical aim of laboratory. Garratt (1997) argues that practical work should be aimed at providing an opportunity to develop technical, observational, manipulative, interpretive, presentational, and communicative skills. While these aims may seem exhaustive, Kirschner (1992) intimates that the objective of laboratory should not only be about technical skills and collecting data, but more about cognitive skills. He emphasises the difference between teaching science *as* inquiry and science *by* inquiry. Laboratory education ought to be delivered with the former in mind, and here lies the crux of teaching the nature of science as a part of laboratory pedagogy, which will be discussed in the second half of this chapter.

Pre-laboratory work plays an important role in developing the aforementioned skills, as it builds students' confidence in understanding the processes that they are going to do (Kirk & Layman, 1996), which they carry into the laboratory (Nichols, 1999). This in turn saves time in the laboratory, which they can spend on other aspects of learning. As Rollnick *et al.* (2001) reiterate, the possession of manipulative skills is important so they can concentrate on thinking about the task rather than handling apparatus. In a premise where so much information and impression are presented in a three-hour period, chunking of information would be very helpful.

2.4.1.3. Raising awareness of safety in laboratory. Safety is paramount to the success of any laboratory enterprise. The multitude of chemicals and their various properties entail risks of hazard to health and disastrous accidents. Several laboratory instruments can also be dangerous without proper and professional care when operating them. Before students are even allowed to enter the laboratory, they have to be fully aware of all safety issues concerning their particular experiment and laboratory in general. This aspect can be thoroughly presented in a pre-laboratory, which may be a part of a laboratory manual or pre-laboratory exercises. An adequate laboratory preparation should improve students' understanding of and efficiency in performing the lab experiments as well as increase laboratory safety (Starkey & Kieper, 1983). Meester and Maskill (1995) go even further by asserting that students are required to assess safety aspects, in order to minimise hazard risks. This can be done in the form of submitted data sheet, in which students should demonstrate they

know what to do in an emergency situation (Povey & Bennett, 2000; Starkey & Kieper, 1983).

In their study on hygiene and safety in chemistry laboratory, Miller *et al.* (2000) found that in many universities, safety education in chemistry has been relegated primarily to a few regulatory documents at the beginning of a laboratory course, or an occasional warning in the description of a specific experiment in a pre-laboratory lecture. Moreover, safety issues are seldom raised in general chemistry or organic chemistry lecture-based chemistry courses. They argue that this is not sufficient, and therefore propose a separate chemical safety education to ensure that this issue is addressed. They suggest several text-based resources, but also concede that they may not be entirely relevant. To solve this problem, they argue that course designers should embed safety education into a pre-laboratory, combined with internet search assignments.

Upon investigating chemistry undergraduate students at an American university, Polles (2006) revealed that students thought they were not adequately prepared for safety issues. When asked about their overall laboratory experience, they surprisingly did not mention any safety issue initially. It was the experience of dealing with irritating fumes and strange smells that made them realise how important it was to address safety issues properly.

2.4.1.4. Enhancing affective experiences. In roughly the last two decades, the affective domain in chemistry education has been increasingly gaining more attention, as students voice their concerns about their university experience. Annual student surveys at times offer an illustration of how the learning goals set by course designers are often surprisingly disconnected from students' actual learning experience. They feel demotivated, disinterested, and, to some extent, disoriented as to what they really learn from their laboratory work. Barrie *et al.* (2015) assert that motivation is key to improving students' attitude to laboratory. Their 15 years' worth of development work on student experience survey in undergraduate science laboratory reveal that relevance of laboratory experience to the real world is viewed as a motivating factor. Interest and responsibility for own learning are also key to the positive attitude towards laboratory.

Johnstone and Al-Shuaili (2001) contend that laboratory work must be delivered to nurture interest in and enjoyment of the subject, confidence in own ability, and motivation to learn. Echoing this, Galloway *et al.* (2016) also maintain that undergraduate chemistry laboratory ought to provide an opportunity for meaningful learning. In order to reach that goal, cognitive, affective, and psychomotor aspects of learning must be brought together in an integrated and concerted fashion. In another study, Galloway and Bretz (2016) assert that '[t]eaching students the role of the affective domain and to not be afraid of the challenges of learning could increase the opportunities for meaningful learning in the laboratory' (p. 152).

The rather rich and descriptive findings from Galloway *et al.* (2016) demonstrate that students feel more confident when they have a sense of control of what they do in the laboratory. A part of this is triggered by a more open-ended nature of an experiment, and other part is ascribed to pre-laboratory tasks. From this point of departure, pre-laboratory is designed to give the students a glimpse into the relevance and exciting aspects of laboratory. Starkey and Kieper (1983) found that students felt more confident in the laboratory because they knew exactly what they were doing. In the end, their confidence was one of the factors that made their laboratory experience enjoyable.

Within the affective domain, motivation is also indispensable because it plays an important role in students' conceptual change processes, critical thinking, learning strategies, and science learning achievement (Tuan, Chin, & Shieh, 2005). When given due credit, such as a small percentage of mark, pre-laboratory exercises also motivate students to study before a laboratory session (Pogačnik & Cigić, 2006). Tuan and colleagues used six factors of motivation in their validated questionnaire design, *i.e.*

- self-efficacy; students believe in their own ability to perform well in science learning tasks
- active learning strategies; students take an active role in using a variety of strategies to construct new knowledge based on their previous understanding
- science learning value; to let students acquire problem-solving competency, experience the inquiry activity, stimulate their own thinking, and find the relevance of science with daily life
- performance goal; to compete with other students and get attention

- achievement goal; students feel satisfaction as they increase their competence and achievement during science learning
- learning environment stimulation; such as curriculum, teachers' teaching, and physical setting

2.4.2. Various Forms of Pre-laboratory Activities

Traditionally, laboratory manual has been used as a primary source of preparation for laboratory (Hofstein & Lunetta, 1982). The laboratory manual plays a major role in defining goals and procedures for laboratory activities. Ideally, it is also supposed to help focus observations and the development of inferences, explanations, and other activities in laboratory investigation. In some cases, it also refers students to a scientific paper that is meant to be used as a framework to discuss how the students would tackle the problem which is addressed by the paper (Garratt, 1997). In other cases, it constitutes an entire module on its own that contributes to the whole laboratory course, such as the one developed by Schmid and Yeung (2005). Their online pre-laboratory work can be accessed by students off campus at any time to allow students some timetabling flexibility whilst offering the university a cost effective means of delivery. Each module is set in the context of a real life problem, which students work to solve in a virtual environment. Students make decisions regarding experimental design, observe simulations of reactions (both at macroscopic and molecular levels), record and interpret data, perform calculations and draw conclusions from their results.

In due course, pre-laboratory has been evolving into various forms and modes of delivery. The following subsections will explore some of these.

2.4.2.1. Pre-laboratory lectures. Pre-laboratory instructional programmes tend to vary in their scheduling formats and content emphasis. The direct approach is the traditional short lecture presented at the start of the laboratory period. Here, theory relevant to the experiment is reviewed, time permitting. But generally, the emphasis is placed on discussion of laboratory procedures directly related to the experiment (Fine *et al.*, 1977). In its traditional form, there is little time for student-teacher interaction and no time for the students to reflect on the laboratory after the pre-laboratory lecture was completed (Isom & Rowsey, 1986). Fine *et al.* (1977) concede

that serious disadvantage of this instructional format is its infringement on scheduled laboratory time.

One of the most recent publications surveyed by Agustian and Seery (2017) described the use of pre-laboratory video lectures to introduce concepts in advance of the upper-level undergraduate laboratory sessions (Schmidt-McCormack *et al.*, 2017). The rationale for this approach was to overcome timetabling issues that meant pre-laboratory lectures had been presented several weeks prior to the laboratory session, as well as that some students may have had to complete the laboratory before attending the corresponding lectures. A common theme across all pre-laboratory activities is that it offers a structure upon which students will focus their efforts.

2.4.2.2. Discussions. According to Kirschner (1992), group discussion is an invaluable aid in getting students to think about the experiment they are going to conduct; to explore its nature and its implications more deeply. It encourages students to reflect upon past personal experience and to use it as a means to discover and evaluate solutions to present problems. Rollnick *et al.* (2001) used two forms of pre-laboratory preparation—pre-laboratory questions and synopses, both in conjunction with pre-laboratory discussions. The pre-laboratory discussions were mainly to clarify any misunderstandings that may be prevalent, to consolidate ideas and help to remove any ambiguity that might be in the instructions. To prepare for a prelab discussion, students could be asked to prepare several questions. Smith (1987) contends that the main value of using laboratory questions to prepare for an experiment is specificity: The questions cover information that this particular class needs to know right now in order to understand and perform the experiment successfully.

A model for increasing and formalising the amount of pre-laboratory discussion was reported for a traditional Hess's Law experiment, with the authors reporting that students had a much better grasp of core concepts as a result of the formalised discussion (Davidowitz, Rollnick, & Fakudze, 2003). A related model where students had to do some pre-laboratory planning before coming to the inorganic chemistry lab, and subsequently use this planning as a basis for discussion with a demonstrator before beginning practical work was reported (Johnstone *et al.*, 1994). Students

reported that the pre-laboratory preparation helped them understand what was occurring in the lab, as well being useful for their post-laboratory analysis (Agustian & Seery, 2017).

2.4.2.3. Pre-laboratory quizzes. In its early development, prelab quizzes were designed to ensure that students were adequately prepared for the laboratory by means of testing their theoretical, methodological, and safety-related competence (Kolodny & Bayly, 1983; Starkey & Kieper, 1983; Valeriotte, 1976). In practice, it was apparent that they were not a completely adequate assessment of the students' understanding of the experiments (Valeriotte, 1976), as the vast majority of these were directed at learning the theory (Pickering, 1987). Nowadays, quizzes often are a part of a pre-laboratory suite, along with other forms such as prelab videos (McKelvy, 2000), prelab assignments (Gammon & Hutchinson, 2001), and online prelab tutorial (Koehler & Orvis, 2003).

Quizzes with questions designed to improve links between theory and practical work by means of providing immediate feedback to students were described for students in general chemistry courses (Chittleborough *et al.*, 2007). Correct responses were reinforced, while incorrect answers prompted some guiding feedback, with students being allowed a second attempt. The overall exercise was worth 2% of the laboratory mark, but evaluation indicated that students appreciated the feedback cycle and felt it helped their learning. In addition, reflecting earlier work, students reported that it "forced" them to prepare in advance. Pre-laboratory quizzes that presented different questions to different students were also reported (Gammon and Hutchinson, 2001), although in this case they were hand-graded with feedback after the event (Agustian & Seery, 2017).

2.4.2.4. Pre-laboratory videos. Researchers have used videos for laboratory demonstrations since the 1970s, to help students learn manipulative skills. See for example, Neerinck and Palmer (1977). Learning gains were observed among students who were exposed to this kind of instruction. When used as a demonstration method for the entire experiment, Russell (1984) argues that pre-recorded videos are advantageous because demonstrations that occur on a scale too small to be seen in the live lecture can be magnified by close-focus techniques. Also, demonstrations

that are too dangerous for the live lecture can be filmed outside the classroom. At present, most pre-laboratory videos can be easily accessed online, such as the one shown in Figure 8.

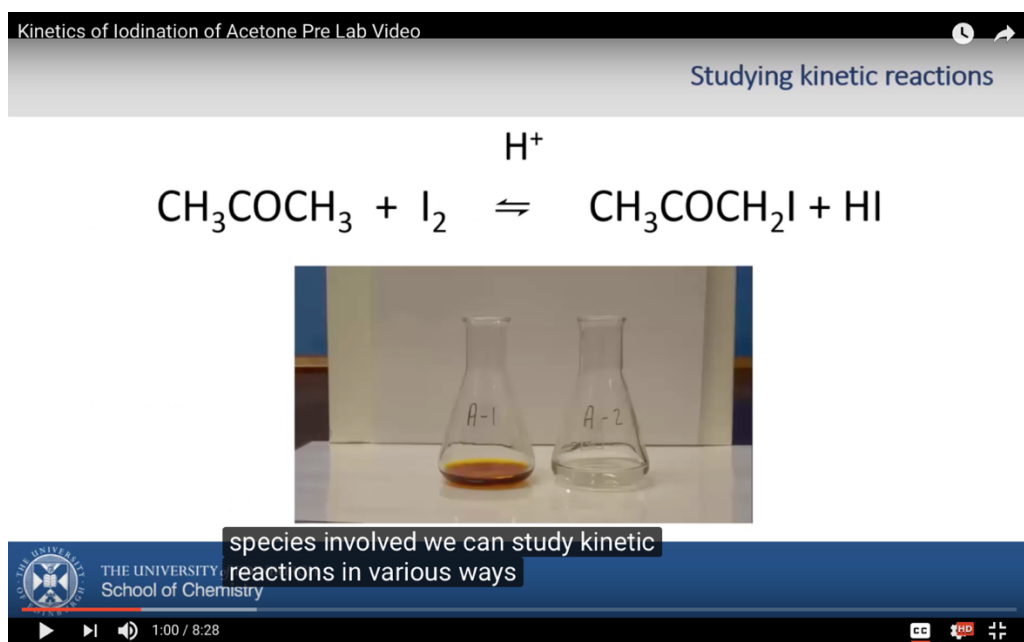


Figure 8. A typical pre-laboratory video on theoretical background and technical demonstration (courtesy of School of Chemistry, The University of Edinburgh)

The use of video became increasingly popular (Agustian & Seery, 2017). A report in 1993 stated that nine of the seventeen UK universities responding to a survey reported that they used videos in their laboratory courses for teaching materials (Meester & Maskill, 1995). An approach to designing these videos was published at this time. Researchers videoed students completing a procedure, and completed an analysis of the videos to identify errors. These were found to fall into the categories: preparation of equipment; level of care taken and concern for accuracy; and students performing procedures ‘without thinking of the likely consequences of their actions’ (McNaught *et al.*, 1993). These were used to design simulations which included video clips on technique. The approach led to a reported improvement in performance of technique.

In another study, the times required for students to complete a kinetics experiment were measured for three different scenarios, with each one having a different format preparatory information. In the first, students were provided with written instructions. In the second, students were given video instruction where the

text was presented as audio to augment pictures of what is being described. And in the third, students were provided with an interactive computer programme which included videos (Burewicz & Miranowicz, 2006). The researchers found that the time spent on preparation was shortest for written instruction, but that students assigned to the video and interactive groups were much more efficient in their practical task, especially with regards to setting up apparatus, using software and taking measurements. Students who were given only written preparatory material made almost 6 times as many mistakes as those who received video and interactive preparation, and were over 4 times more likely to complete tasks incorrectly or with uncertainty. Overall the authors report that manual activities were assisted equally well by video and interactive activities, while training in computer programme use was best assisted by preparation using interactive activities. No difference between formats was observed with regards to theoretical preparation. While video has a long history, its use in the last two decades has expanded dramatically and some recent examples representing current approaches are summarised (Agustian & Seery, 2017).

Echoing early work, use of videos in organic chemistry were found to increase the post-test laboratory quiz scores of students who had watched videos compared to those who didn't, and these students also completed the practical work more quickly (Nadelson *et al.*, 2015). These authors observed a pre-/post-test quiz score increase of over 10% for students who had watched videos, compared to 4% for those who hadn't. Nadelson's work was grounded in transfer of knowledge – the transfer of task-specific knowledge by means of experts modelling or demonstrating a process for novice learners. This expert-modelling approach was used in a study on the value of preparative videos for teaching laboratory skills (Seery *et al.*, 2017). Students were required to use these exemplar videos as a basis for preparing videos of their own techniques in the laboratory class. The intention was grounded in the literature on formative assessment, advocating the provision of exemplary approaches so that learners could consider their own work in comparison to the exemplar, and make any changes prior to presenting their work for assessment (Hendry, 2013; Sadler, 1989). Analysis found that students' ability to answer technique-related questions improved as a result of the process.

Similar findings were reported by Powell and Mason, who reported that students in general chemistry who had access to video (described as podcasts) needed fewer scaffolding interactions in the laboratory compared to those who didn't, and these students were able to acquire their results more efficiently (Powell & Mason, 2013). Students using video preparation were reported to need less support in an organic chemistry laboratory compared to students who received in-laboratory instruction from teaching assistants (Jordan *et al.*, 2015).

A parallel study also explored the different types of video that students found most useful (Box *et al.*, 2017). Videos relating to technique (microscale distillation), use of instrumentation (GC), and calculation based on instrumental (GC) output were prepared; each of the three being relevant to an experiment students were to complete. Students' responses to questionnaire were better in the experimental group, and in particular a large effect size was noted for the questions associated with use of instrumentation (GC), although students themselves ranked the techniques video most useful. It was observed in both studies that students who watched videos spent less time on the tasks in the lab.

Tan and co-workers described the implementation of videos via a framework of flipped teaching, offering students video in advance of laboratories in introductory inorganic chemistry and an organic chemistry lab, both involving the provision of videos about synthetic procedures (Teo *et al.*, 2014b). The 'flipped' framework, increasingly common in lecture courses (Seery, 2015), was used here to explicitly ensure links between pre-laboratory work and in-laboratory work were tangible. Interviews with students suggested that the videos helped "unpack" written laboratory procedures that students found difficult to interpret by means of showing the videos in practice. In addition, while the focus was on improving technique, students reported that they also felt more comfortable with the underpinning theory as a result of watching videos in advance, mirroring the findings of (Winberg & Berg, 2007). Fung also describes the use of pre-laboratory videos as "flipped", and outlines a novel procedure for creation of first-person perspective videos (Fung, 2015).

At present, videos tailored for a particular experiment have been used as a prelab, *e.g.* for upper-division undergraduate chemistry (Schmidt-McCormack *et al.*, 2017; Seery *et al.*, 2017), generated by students (Box *et al.*, 2017; Jordan *et al.*, 2015),

in combination with e-quizzes (Galloway & Bretz, 2016; Jolley *et al.*, 2016), and to help students for whom English is not the first language (O'Sullivan & Harrison, 2016).

2.4.2.5. Interactive simulations. Meester and Maskill (1995) argue that simulations can serve several purposes, such as preparing students for a laboratory experiment and the corresponding techniques, responding to idiosyncratic needs of individual students by means of immediate feedback, facilitating laboratory performances, and increasing the efficiency of instructions. These can be used as a preparation for laboratory work, or to carry out a virtual investigation (Garratt, 1997), an example of which is shown in Figure 9.

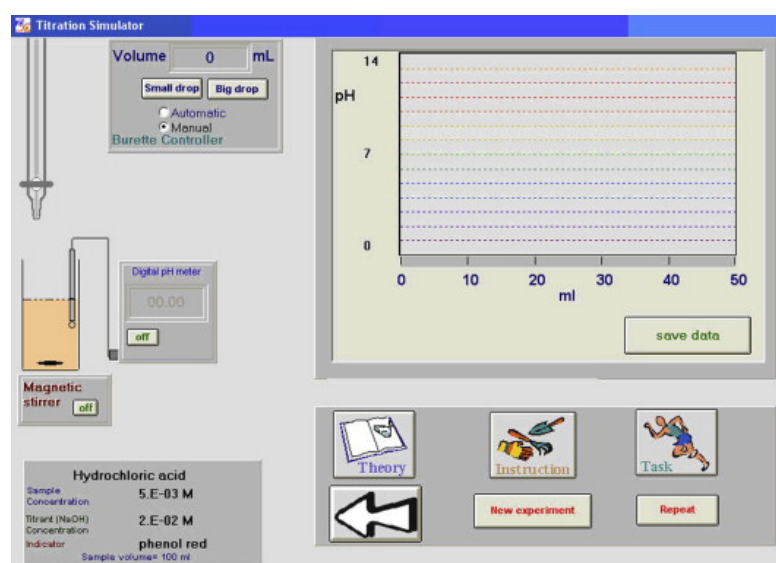


Figure 9. Titration simulation as a pre-laboratory activity (Limniou *et al.*, 2009)

When used as an entire virtual investigation on its own, a simulation can decrease risk of personal injury (Moore *et al.*, 1980). Dangerous but valuable experiments can be simulated easily to give the student the benefit of an experience without the risk. When designed as a prelab, Moore and colleagues also found that under a simulation, students' errors can be found and corrected before the mistakes become habits in the real laboratory.

When used as a prelab, Winberg and Berg (2007) used a simulation on buffers to prepare students for a pH laboratory that allowed students to vary experimental parameters and found that as a result of the simulation, students asked more theoretical questions compared to those in a control group. Kirschner (1992) concedes, however, that these benefits accrue when simulations are used as a

surrogate for 'real' laboratories as opposed to a viable form of laboratory activities in its own right. The use of the software should be intended to augment laboratory sessions, not to replace them (Povey & Bennett, 2000).

2.4.2.6. Experimental plans. The purpose of an experimental plan is to organise students' thinking about each experiment before coming to the laboratory (Johnstone *et al.*, 1994). Central to this approach is the development of specific, detailed written experimental procedures to accomplish the desired goals of an experiment (Merritt *et al.*, 1993). Merritt and colleagues found that the incorporation of an experimental design component has successfully increased students' interest, enthusiasm, and active participation in the laboratory. This form of pre-laboratory activities can be implemented in various layouts, such as flow diagrams (Anderson, Randle, & Covotsos, 2001) and synopses (Rollnick *et al.*, 2001). Some relationship between the quality of flow diagrams and confidence in carrying out the experiment has been observed (Davidowitz & Rollnick, 2001).

2.4.2.7. Mental preparation. Similar to the previous form, mental preparation refers to the organised foreshadowing of laboratory activities. It is based on the mental rehearsal of the steps of a skill, having been provided with a description and illustrations before performing it (Meester & Maskill, 1995). McKelvy (2000), citing Johnstone, argues that mental preparation is a prerequisite of any laboratory activities and it must be carefully thought out as the course itself. In the review of pre-laboratory research, Agustian and Seery (2017) found that most of the studies in chemistry laboratory education on mental practice are reported by Beasley (Beasley, 1979, 1985; Beasley and Heikkinen, 1983). This involved prompting students to think out in their mind the steps they will complete in an experimental technique and to relate these steps to an illustration provided. No difference was found in performance between students who completed mental practice alone, physical practice, and mental and physical practice, but that there was a difference between these treatment groups and the control group. That is to say, some form of practice had an effect.

2.5. Feedback and Assessments in the Laboratory

Assessment is an essential element in education whereby information about student learning is collected systematically and action or intervention is performed accordingly. It is commonly agreed that the ultimate goal of assessment in education is to improve learning.

The laboratory in chemistry education is a unique mode of instruction that requires a unique mode of feedback and assessment, whereby validity and reliability are taken into account. In this regard, Hofstein and Lunetta (1982) contend that more sensitive evaluation instruments that will provide information about what students actually do and learn in the laboratory are therefore required. Such instruments should also measure students' competence in developing inquiry skills and other laboratory-related skills argued in the beginning of this chapter.

Feedback and assessments are not only evaluation measures to gauge students' progress. They are also a form of reward, provided that there are some well-defined criteria for each progress they make. Accordingly, students have a right to know which criteria contribute to the mark on the experiment and how the weightings of these marks determine the overall mark for the course. Ideally, both of these schemes should be described in a separate part of the laboratory manual. This is rarely done, unfortunately (Meester & Maskill, 1995). Fair and transparent reward schemes are important, if students are to take laboratory work seriously (Johnstone & Al-Shuaili, 2001).

It is fair to reassert that there is a difference between feedback and assessment. The former is usually ungraded and provided frequently so that students can improve the quality of specific aspects of their learning whilst laboratory instructors can evaluate the effectiveness of different pedagogical strategies. The latter refers to criterion-referenced evaluation of students' performance, which is usually graded and done continually (Fink, 2013).

In his work on an integrated approach to designing college courses, Fink proposes a triangular model for feedback and assessments in relation to learning goals and pedagogical activities, as shown in Figure 10. The three ellipses refer to curricular decisions that need to be made, which are connected by double-headed

arrows, reflecting reciprocity and interconnectedness. Situational factors at the bottom refers to information that needs to be gathered, with arrows coming up indicating that this information should be used in the process of making the three key sets of decisions.

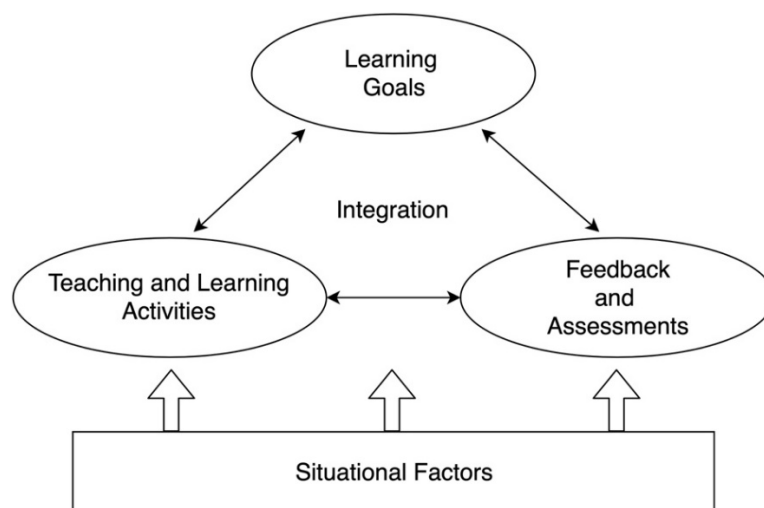


Figure 10. Key components of integrated course design (Fink, 2013)

In the context of laboratory education, Hofstein and Lunetta (2004) argue that explicating goals for students' specific learning outcomes should serve as a principal basis upon which teachers design the laboratory assessment. They assert that the almost simultaneous emphasis on conventional paper and pencil assessment (not performance assessment) has almost certainly had a negative effect (Bryce & Robertson, 1985). If students should exhibit:

- appropriate manipulative skills;
- the power to observe;
- the ability to interpret observations and results; and
- the ability to plan experiments,

then the conventional laboratory report, upon which the assessment is commonly based, can possibly make some kind of measurement of the second and third categories above, but is not 'designed' to handle the first and the last (Johnstone & Al-Shuaili, 2001).

Various forms of laboratory assessment have been used, such as practical tests, written reports, end-products (such as synthesised compounds and chromatogram), performance of laboratory skills, paper-and-pencil tests, and interviews (Meester & Maskill, 1995). Each form addresses different aspects of laboratory and should

therefore be used in a concerted and integrated manner. In the following subsections, each of these forms of assessment will be discussed under categories of formative and summative assessments, as well as direct and indirect assessments.

2.5.1. Formative and Summative Assessments

The most common form of student learning evaluation at university level is summative assessment, in which students are tested cumulatively at the end of a course or halfway through. The tests are graded and usually account for a large contribution to the final mark of the corresponding course. Contrastingly, formative assessment is conducted throughout the course, by means of giving constructive feedback to guide students in their learning. Formative assessments are not always graded but they are just as important as, if not more than, summative assessments.

This is also the case in the undergraduate chemistry laboratory. In nearly all universities laboratory skills have been assessed by using just the outcomes, such as reports and samples, and not by any observation of the actual performance of the laboratory work itself in a real situation (Hofstein & Lunetta, 1982; Meester & Maskill, 1995). More recent development in laboratory education, such as that of Seery *et al.* (2017) and Hensiek *et al.* (2017), providentially makes a stronger case for more implementation of formative assessments in the laboratory, as they enable students to bridge the gap between their current level of understanding and the desired level, as well as encourage them to monitor the quality of their own work during actual laboratory performance. In the context of online-based laboratory resources, formative assessments also allow instant feedback to students and thereby enable them to get a deeper understanding of concepts underlying the practical tasks (Schmid & Yeung, 2005).

Appropriate, timely, and effective feedback is important. Flexible offering of pre-laboratory preparation can also effect capacity to provide real time formative feedback and enhance learning outcomes. The capacity to implement formative assessment of student comprehension by means of online quizzes provide opportunity for students to receive immediate feedback on their demonstrable comprehension of theoretical, mathematical, procedural and safety-related laboratory elements (Gregory & Di Trapani, 2012; Nicholls, 1999)

2.5.2. Direct and Indirect Assessments

The distinction between direct and indirect assessments lies in the way learning is measured and recorded. According to Weldy and Turnipseed (2010), indirect measures of learning refer to students' perceptions of what they have learnt, which are usually assessed with surveys, interviews, and focus groups. Insights from such measures are valuable for aligning the curriculum with stakeholders' expectations. Elbeck and Bacon (2015) assert that only when they are related to learning can such measures be called indirect assessment. Conversely, direct measures of learning refer to evidence and artefacts related to students' learning, such as course-embedded assessments (case studies, portfolios, projects) and performance demonstration (standardised written tests, oral exams, presentations).

In their work on a universal definition of direct and indirect assessments, Elbeck and Bacon (2015) conclude that experts in educational assessments generally agree on the emphasis of scoring and association with learning objectives in distinguishing both forms of assessments. They used a flowchart to determine whether an assessment is direct or indirect by nature, as shown in Figure 11. Building on previous literature and expert consultations, they redefined the terms as follows:

- Direct assessment: Scoring a student's task performance or demonstration as it relates to the achievement of a specific learning goal.
- Indirect assessment: Measures which are assumed to be related to learning that do not involve scoring learner task performance or demonstration.

In the chemistry teaching laboratory, students have to exhibit manipulative skills to an assessor, which is usually a demonstrator. For this to operate fairly, each demonstrator has to have some objective and criterion-referenced measure of the skills to be assessed (Johnstone & Al-Shuaili, 2001). This form of direct assessment can also take form as observational assessment. Hofstein and Lunetta (2004) describe several observational assessment methods developed in the 1970s and 1980s. Using certain criteria, the researchers or teachers unobtrusively observe and rate each student during normal laboratory activities. They assess students according to the following broad phases of activity: (1) planning and design, (2) performance, (3) analysis and interpretation, and (4) application.

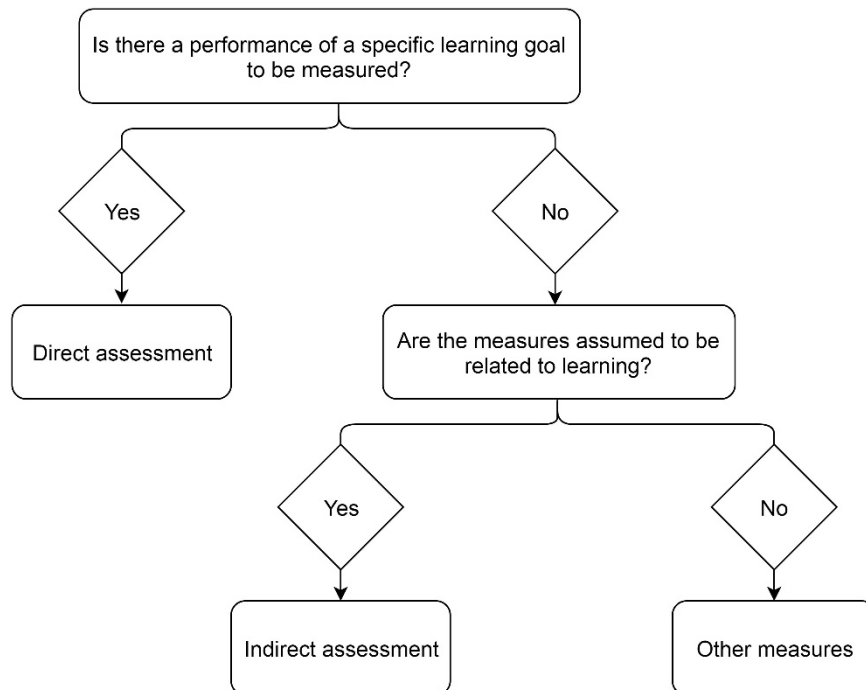


Figure 11. Direct and indirect assessments flowchart (Elbeck & Bacon, 2015)

While graded, direct assessments are common in educational practice, indirect assessments are common in educational research. In an educational research project where learning is central to the investigation, indirect assessments should be taken into account, as they will define which methods and instruments are to be used to gauge student performance. This form of assessment requires a student to report on their own learning, by rating their knowledge or skills. The results of indirect assessment can be quantified in a similar way survey results are quantified. Although they are not in terms of academic scores, such results reflect students' achievement too. Hofstein and Lunetta (2004) argue that the effects of laboratory experiences on students' interest and motivation should also be assessed. Ever more calls for addressing the affective dimensions of learning render indirect assessments more relevant and necessary.

Part 2. Nature of Science

The terminology 'nature of science' typically refers to the epistemological commitments underlying the activities of science, *i.e.* science as a way of knowing, or the values and beliefs inherent to the development of scientific knowledge (Abd-El-Khalick & Lederman, 2000). It also entails an understanding and appreciation of the work of scientists, processes of science, and sociology of science (Yacoubian & BouJaoude, 2010). As a concept, it has been in a discourse of science education for well over a century (Russell & Weaver, 2011). Ernst Mach (1838–1916), philosopher, physicist, and science educator, is believed to be the first to promote an understanding of what we now describe as the nature of science (Matthews, 1994). Mach believed that scientific theory is an intellectual construction for economising thought and therefore it can only be understood if its historical development is understood. The decades from 1950 to 1980 also represent a period of paradigm shift and significant changes in thinking about the nature of science and science education (Brodbeck, 1961; Cooley & Klopfer, 1961; Kuhn, 1962; Rowe, 1978; Schutz, 1967; Taber, 2017a; Welch & Pella, 1967). Novel insights in philosophy of science, new findings from cognitive psychology and pedagogy contributed to a questioning and rejection of accepted views, *e.g.*, logical positivism in philosophy and behaviourism in the learning sciences (Duschl & Grandy, 2013).

As an area of research, nature of science (NoS) encompasses the field of epistemology, a branch of philosophy that is concerned with how scientific knowledge is generated and how it shapes the character of science. In its development, scholars and researchers in this interdisciplinary field come from a diverse background. Among philosophers, NoS debate has traditionally revolved around investigations of the epistemological, methodological, and ontological commitments of science. But there are illuminating, non-philosophical studies of science, such as conducted by historians, cognitive psychologists, sociologists, economists, anthropologists, and numerous other disciplines (Khine, 2012). NoS is a fertile hybrid area that blends aspects of various social studies of science. Taber (2017a) refers to this interdisciplinary research as *Science Studies*. Currently, the corpus of knowledge in NoS provides a rich description of what science is, how it

works, how scientists operate as a social group and how society itself both directs and reacts to scientific endeavours.

In investigating science and scientists, NoS researchers raise questions originating along the line of “What, if anything, demarcates science from other human endeavours?”, “Are science ideas discovered or invented?”, and “How is consensus reached in the scientific community?” (McComas, 2002). The nature of science is not particularly concerned with the natural world in the way that science itself is, at least not directly. That is to say, a researcher in NoS is more focussed on finding out how the law of thermodynamics came to exist than how it works in the laboratory. They are more concerned with the implication of atomic theory development on the tentativeness of scientific knowledge than, for example, how atoms behave in the centre of a star.

Why is it important to teach NoS in undergraduate chemistry courses? What exactly are the aspects of science that students should learn in the chemistry laboratory, considering they learn how to do science? Do they actually know the underlying assumptions of the observations they conduct in the lab, the data they gather, and the interpretation thereof? To what extent does the current laboratory education address the problematique around NoS? Is there any way to develop a more pedagogically-valid and philosophically-informed laboratory curriculum? These questions will be underpinning the rest of this chapter, and indeed, illuminating the entire research. First, current state of research and practice in NoS will be reviewed, followed by a redefinition of the term for the context of laboratory education.

2.6. Current State of NoS Understanding

NoS understanding is increasingly becoming an important science learning outcome, particularly for preservice science teachers and science majors (Schussler *et al.*, 2013). The caveat is, however, NoS concepts are not easy to measure and, above all, they are not only difficult for students to grasp but also difficult to define. For this reason, most studies on nature of science use qualitative instruments (Caussarieu & Tiberghien, 2017; Eymur, 2019; Kang & Wallace, 2005; Lunde, Rundgren, & Drechsler, 2016; Russell & Weaver, 2011). In my review of six decades of research development in NoS, more than half of the published studies are

qualitative, deploying semi-structured interviews as their main source of data, along with group discussions, semi-structured observations, and open-ended questionnaires.

In order to gauge the degree to which the contemporary science education is informed by the research in NoS, several studies and reviews will be highlighted in this subsection. Towards the end of the 20th century, DeBoer found that the positivist view of the philosophy of science from the 19th century still informed much classroom practice and pervaded most available curriculum materials (DeBoer, 1991; McComas, 2002). Two decades later, Abd-El-Khalick (2012) found that there was a global indication that elementary, middle, high school, and college students, as well as teachers continue to ascribe to naïve views of NoS.

According to McComas (2002), many science educators claimed to have taught NoS in their practice. However, data analyses scarcely revealed explicit reference to NoS in their planning and instruction (Abd-El-Khalick, Bell, & Lederman, 1998). Even more dreary, for most science students, a description of NoS, if any, is relegated to a few paragraphs at the beginning of the textbook quickly glossed over in favour of the facts and concepts that cram the remainder of the book. And the ideas put forth in textbooks concerning the nature of science are almost universally incorrect, simplistic, or incomplete (Bentley & Garrison, 1991).

Having analysed more than 2000 responses, Ryan and Aikenhead (1992) concluded that students confused science with technology. They only had superficial understanding of the private and public aspect of science and how scientific knowledge was influenced by sociocultural values. In numbers, they reported that:

- 46% held the view that science could rest on the assumption of an interfering deity;
- Only 17% were certain of the inventive character of scientific knowledge;
- 19% believed that models are actual copies of reality;
- Only 9% chose the contemporary view that scientists use any method that might get favourable results; and
- 64% of students expressed a simplistic hierarchical relationship in which hypotheses become theories and theories become laws, depending on the amount of “proof behind the idea.”

Five decades after the prolific studies on curriculum reform in science education (Carey & Stauss, 1968, 1970; Cooley & Klopfer, 1961, 1963; Kimball, 1968; Welch & Walberg, 1968), the literature unfortunately still shows that students and teachers have an inadequate epistemological understanding of the nature of science (Niaz, 2016). In their review of high school chemistry textbooks, Abd-El-Khalick, Waters, and Le (2008) inquire into the representations of NoS and the extent to which they have changed in the past four decades. Their study focussed on the empirical, tentative, inferential, creative, theory-driven, and social aspects of NoS. Fourteen textbooks were analysed. Relevant textbook sections were scored on NoS aspects reflecting the accuracy, completeness, and manner (explicit versus implicit) in which these aspects were addressed. They found that textbooks fared poorly in their representations of NoS.

According to Abd-El-Khalick (2012), the current state of affairs is caused by a host of factors, including the complexities associated with bringing about significant and systemic change to the beliefs and practices inherent to science education. Making headway with an especially challenging domain, such as teaching and learning about NoS, necessitates synergistic, long-term research and development efforts. Also, the domain of NoS largely remains a field of scholarship for non-practicing scientists. The overwhelming majority of practicing scientists do not have active research programmes that address epistemology of science (Abd-El-Khalick, 2012).

2.7. Arguments for NoS in Laboratory Education

Science has a pervasive, but often subtle, impact on virtually every aspect of modern life—both from the technology that flows from it and the profound philosophical implications arising from its ideas. However, despite this enormous effect, few individuals even have an elementary understanding how the scientific enterprise operates. This lack of understanding is potentially harmful, particularly in societies where citizens have a voice in science funding decisions, evaluating policy matters and weighing scientific evidence provided in legal proceedings. At the foundation of many illogical decisions and unreasonable positions are misunderstandings of the character of science (McComas, 2002). The argument is

that teaching about the nature of science is essential to a science education that wishes to prepare future scientists, cultured members of society, and informed citizens, and that accordingly great care is needed to balance the teaching about science itself as a cultural and intellectual activity, and teaching about some of the important, fascinating, and highly applicable, scientific knowledge that this cultural activity we call science has produced (Taber, 2017a).

The advancement of the learning sciences and our deeper understanding of cognitive psychology has led us to recognise and seek coordination of a triad of practices—cognitive, epistemic and social—in the learning of science (Duschl & Grandy, 2013). Acquiring conceptual knowledge (*e.g.*, theoretical chemistry content) should not be separated from learning science practices (*e.g.*, processes of science). The emerging consensus is that science learning and teaching ought to be grounded in epistemological, social structures, and practices.

Understanding NoS seems to be a cognitive learning outcome that needs to be planned and explicit. The research literature shows that many science education researchers have incorporated reflective elements in their attempts to teach NoS explicitly to middle school students in regular science classrooms (Colagrande, Martorano, & Arroio, 2017; Lunde *et al.*, 2016; Mulvey & Bell, 2016; Williams & Rudge, 2016) and found these elements effective in enhancing students' views. Nevertheless, the science laboratory as a context for teaching NoS has almost been absent in published research reports (Yacoubian & BouJaoude, 2010).

In his book on NoS and science pedagogy, Robinson provided an overview of the nature of physical reality, aspects of physical description including probability, certainty and causality, and view of the nature of science in various science disciplines. He concluded with considerations for the interplay between science instruction and the nature of science (Robinson, 1968). The teaching of science must explore the interplay between science and the intellectual and cultural traditions in which it is firmly embedded. Science has a history that can demonstrate the relationship between science and the wider world of ideas and can illuminate contemporary issues (Khine, 2012).

Shamos (1995) argues in *The Myth of Scientific Literacy* that while knowledge of science content may not be necessary for obtaining science literacy, understanding

the nature of science is prerequisite to such literacy. The ability to distinguish good science from parodies and pseudoscience depends on a grasp of the nature of science (McComas, 2002). Hodson (1991) cites Dewey's 1916 argument that understanding scientific method is more important than the acquisition of scientific knowledge (McComas, 2002).

Kuhn (1970) argued that initiating science students into disciplinary traditions includes having them take the processes and methods of those disciplines, and consequently the underlying ontological and epistemological values and assumptions, for granted. Putting aside epistemological and ontological issues, and the conviction that the methods at hand will generate valid and reliable knowledge, advanced students and scientists can engage the activities of their science disciplines and invest the time and energy required to vigorously pursue answers or solutions to specific questions or problems related to some restricted aspect of a minute corner of the natural world (Abd-El-Khalick, 2012).

Epistemological and ontological underpinnings do not seem to be crucial to the learning or practice of disciplinary science (at least, according to Kuhn, in periods of "normal" science). For Kuhn, barring periods of intense crises, the very fact that practicing scientists do not tackle epistemological issues is an integral aspect of NoS (Abd-El-Khalick, 2012). Scientists are practitioners within well-established traditions of practice and cannot be assumed —as the evidence shows— to hold coherent epistemologies of the sort sought in philosophically-oriented inquiries, which underlie the conceptions of NoS adopted in this research.

2.7.1. Ontological Arguments

Ontology is a philosophical study of the nature of being, existence and reality. Some of the philosophical problems pertaining to the existence of a god, for example, are problems in ontology. It concerns whether or not an entity exists, but also encompasses problems about the features of and relations between existing entities. In the chemistry laboratory, these are often the problems of theories and concepts: how theories came to exist and how chemical concepts relate to one another. Nersessian (1989) describes how change in science theories, such as theories of

atom, is actually the history of changes in ontology. He argues, 'the ontology of a theory determines what kinds of entities it claims to be about' (pp. 177).

Aikenhead (1987) argues that one vestige of logical positivism is the belief that scientific knowledge connects directly with reality, unencumbered by the vulgarity of human imagination, dogma or judgements. This ontological view is often associated with the idea that science finds absolute truth, and does so independently of the investigator's psychological and social milieu. Such "naive realism," as Nadeau and Desautels (1984) have called it, has been challenged by other philosophical positions.

Having said that, there have been disagreements on this NoS-related matter, including debates between empiricists (e.g., Van Fraassen, 1998) and realists (e.g., Musgrave, 1998) on the ontological status of scientific theories and the entities they often postulate. Nevertheless, Abd-El-Khalick (2012) argue that disagreements about what NoS entails are 'relevant and need to be meaningfully addressed in any framework that aims to guide synergistic research and development efforts' (pp. 68).

Correspondingly, ontological assumptions lie in the heart of a chemical conceptual network. When one of them changes, it will reverberate throughout the network. McComas, Almazroa, and Clough (1998) maintain that when common sense ontology changes into a scientific ontology, abstract entities need to be constructed. As an illustration, Newtonian mechanics initially existed only in mental models, upon observation of the natural world. Changes from observational accounts and properties to being a mathematical relation call for shifting from a concrete to an abstract representation. In laboratory education, this is often the problem that lingers from one curriculum reform to another. Instruction in abstraction techniques is arguably helpful for students to build the requisite scientific ontologies.

Evidence suggests that knowledge of the nature of science assists students in learning science content. For example Songer and Linn (1991) illustrated the importance of students having dynamic rather than static views of science in developing a conceptual understanding of topics such as thermodynamics. The static view of science is the idea that science is a group of facts that are best memorised. The dynamic view of science posits that scientific knowledge is tentative, and the best way to understand this knowledge is by understanding what scientific ideas mean and how they are related. Although the authors did not address the mixed view, they

did find that students with dynamic views of science acquired a more integrated understanding of thermodynamics than those with static views.

2.7.2. Epistemological Arguments

In his case for integrating the nature of science into science education, Taber (2016) argues that science education should be aimed at *understanding* of scientific concepts or ideas but not *belief* in them. He exemplifies his argument by resistance among students and teachers against evolutionary ideas. Students bring their own presuppositions about the world into the classroom. When personal and cultural values are in conflict with scientific ideas, it is completely counter-productive to teach those ideas in a dogmatic manner, so as students believe in them.

In the pursuit of knowledge, science is a dynamic, ongoing, and process-oriented activity rather than a static accumulation of information (Kimball, 1968). The tentative nature of scientific knowledge is therefore essential to be taught explicitly, so that students do not feel threatened and forced to reject deeply held faith that contradicts the new information. In the context of chemistry laboratory education, scientific knowledge encapsulated in multifarious chemical concepts also calls for a similar approach. Cleminson (1990) summarised the way knowledge develops:

- Knowledge of the physical world develops from birth. Its status is temporary insofar as additional experience or instruction may modify such conceptions.
- These personally constructed views about the physical world act as our personal theoretical lenses and determine what, for us, counts as an observation and what counts as an inference.
- Learning new scientific concepts requires a creative act of the imagination.
- Abandoning cherished knowledge, even as a result of exposure to science teaching, is difficult and may be done only superficially.
- We all have conceptions about our physical world, whether they correspond to those of formal science or not. As such they have subjective meaning for us.

When these are taken into consideration in laboratory curriculum design, students are expected to have a stronger grip on the nature of scientific knowledge and concepts. Understanding how science operates is imperative for evaluating the strengths and limitations of science, as well as the value of different types of scientific

knowledge. For instance, science teachers may understand the atomic model, Boyle's law, and evolutionary theory, but may not understand what law, theory, and model mean in the discipline of science. Hence, ridiculous statements like, "evolution is only a theory" or "when such-and-such a theory is proven it will become a law" may result (McComas, 2002).

Scientific knowledge moves on very quickly. Some of the science a person learns in school will be discredited or substantially modified during their adult life. During that life, quite a lot of the science learnt in school will be of limited importance to new developments, and whole new areas of science with major applications will open up that were never mentioned in school as they were unanticipated. What will not substantially change is the nature of science as a cultural activity which produces, evaluates, develops and sometimes demotes, scientific knowledge (Taber, 2017a). Because science is often wrongly perceived primarily as a body of literal truths, entire fields of knowledge are sometimes questioned when single facts are revised. Perceiving science as a process of improving our understanding of the natural world turns the notion of tentativeness into a strength rather than a weakness.

2.7.3. Pedagogical Arguments

The persistence of students' naive ideas in science suggests that teachers could use the historical development of scientific concepts to help illuminate the conceptual journey students must make away from their own naive misconceptions. In other words, teachers' interest in NoS could assist in understanding the psychology of students' learning (McComas, 2002). Matthews (1994) has argued for the inclusion of NoS courses in science teacher education programmes. The examples he provided demonstrate that a firm grounding in the nature of science is likely to enhance teachers' ability to implement conceptual change models of instruction. Studying the process of historical conceptual development in science may shed some light on individual cognitive development (Wandersee, 1986).

Within science education, changes in our understandings of what science is — the nature of science— have influenced our understandings of what's involved in learning and doing science. Conversely, our understandings of what's involved in learning and doing science have influenced our understandings about the nature of

science (Duschl & Grandy, 2013). For example, some of the resistance to conceptual change theory among classroom teachers arises from the mistaken notion that knowledge of the natural world is completely objective —existing independently of the searching individual. This view of science gives the impression that learning is a fairly straightforward process of replacing what is known with that which the scientific community has discovered is right (McComas, 2002). Teachers who view chemistry as a stable body of concepts, principles, and theories, have difficulty finishing the course because they attempt to teach everything as fundamental. In contrast, teachers who perceive chemistry as a constantly developing body of knowledge limit the presentation of topics to those deemed essential.

Taber and Akpan (2016) contend that a good science curriculum needs to not only teach some science, but also teach about science. There needs to be a balance between teaching some of the products or outcomes of science (such as the periodic table; the theory of natural selection; the ideal gas law) and teaching about the processes of science, how science goes about producing new knowledge. The challenge is, shifting from an indirect teaching of the NoS to a direct, explicit pedagogy of science require us to redesign the existing curriculum (Goff *et al.*, 2012).

A sensitivity to the development of scientific knowledge may also make science itself and science education more interesting. Tobias (1990) maintains that a number of potential university science students —those she calls the second tier— lament that science classes ignore the historical, philosophical, and sociological foundations of science. Incorporating the nature of science while teaching science content humanises the sciences and conveys a great adventure rather than memorising trivial outcomes of the process (McComas, 2002).

2.8. Redefining the Nature of Science for Laboratory Education

Research establishes that the nature of science should be taught in science curriculum, including chemistry laboratory curriculum. However, a number of potential problems will have to be anticipated. Taber (2017a) argues that these problems are the reasons why NoS is still not well reflected in science curricula, regardless of many high profile calls for its importance. The following box encapsulates these issues.

- Science is a broad area of activity with different cultures, methodologies, and epistemologies —what is regarded as common to chemistry may not be so to other scientific disciplines; likewise, questions that are essential for NoS in general are not necessarily essential for NoS in chemistry (Vesterinen & Aksela, 2012).
- There is a lack of consensus on how to best understand and teach the nature of science; even with decades of research development in this area, NoS concepts are always contestable and open to interpretation, redefinition, and contextualisation (Khine, 2012).
- Scholarship about NoS from areas such as philosophy, history, psychology and sociology can be quite technical and specialised, and is often too sophisticated for most students as well as teachers (Taber, 2017a).
- There is less expertise amongst science teachers, curriculum developers and textbook and other resource authors, regarding the nature of science compared to the level of expertise in areas of science themselves (Ellis, 2016).

Regardless of the ongoing debates on the nature of science, some efforts have been made to find some common ground on which the concepts can be defined. Lederman and colleagues are some of the most prolific researchers in the field of NoS (Abd-El-Khalick *et al.*, 1998; Abd-El-Khalick & Lederman, 2000; Abell & Lederman, 2007; Lederman, 1992, 2006; Lederman *et al.*, 2002; Lederman & Lederman, 2004; Lederman & O'Malley, 1990; Schwartz, Lederman, & Crawford, 2004). In an attempt to develop research instruments that could better assess students' understanding of NoS, they proposed an operational definition of NoS:

Although the “nature of science” has been defined in numerous ways, it most commonly refers to the values and assumptions inherent to the development of scientific knowledge (Lederman, 1992).

Lederman and colleagues argue that despite the lack of consensus on aspects of science that are universal, inclusive, exhaustive, and true for all science-related disciplines, there are several distinctive aspects of science that can be used as a reference. These are: scientific knowledge is tentative; empirical; theory-laden; partly the product of human inference, imagination, and creativity; and socially and culturally embedded. Three additional important aspects are the distinction between

observation and inference, the lack of a universal recipe-like method for doing science, and the functions of and relationships between scientific theories and laws (Lederman *et al.*, 2002).

However, this was later criticised by Matthews (2012), as he argues, at a surface reading, it would seem that the Lederman group are empiricists and constructivists about theoretical entities in science. If so, this is a mistake, and is not the message about NoS that science teachers should convey. The mistake is not so much the assumption of one philosophical side, constructivism, in this debate but rather giving the impression that there is no debate or no alternative position that can and has been adopted – the realist position. Once again, a concentration on the NoS rather than open discussion and inquiry about features of science leads to this mistake. Matthews contends that these should better be thought of as different features of science (FoS) to be elaborated, discussed and inquired about, rather than nature of science (NoS) items to somehow be learnt and assessed. Each of these features has been richly written about by philosophers, historians and others. But if they are features of science, then there is no good reason why just those seven features are picked out, and not others of the numerous features – epistemological, historical, psychological, social, technological, economic, etc. – that can be said to characterise scientific endeavour, and that also meet the three criteria of accessibility, consensus and usefulness that the Lederman group additionally utilise to reduce NoS matters to classroom size (Khine, 2012).

The positive side of the list is that it puts NoS into classrooms; it provides researchers with an instrument for measurement of NoS learning; and it can give teachers and students some NoS matters to think through and become more knowledgeable about (Matthews, 2012). The negative side is that the list can, despite the wishes of its creators, function as a mantra, as a catechism, as yet another something to be learnt. Instead of teachers and students reading, analysing, and coming to their own views about NoS matters, the list often short-circuits all of this. And in as much as it does so, it is directly antithetical to the very goals of thoughtfulness and critical thinking that most consider the reason for having NoS (or the history and philosophy of science) in the curriculum (Khine, 2012).

2.9. Aspects and Features of Science in the Laboratory

Similar to scientific knowledge, conceptions of NoS are tentative and dynamic: they have changed (and continue to change) throughout the development of science and systematic thinking about its nature and workings (Abd-El-Khalick, 2012; Duschl & Grandy, 2013). On one side of the debate is the position that NoS should be benchmarked using domain-general, consensus-based aspects of NoS and taught through explicit references to a set of heuristic principles that philosophers and historians of science use to characterise science as a way of knowing. On the other side of the debate is the position that science, as well as science education, should be conceptualised in terms of cognitive, epistemic, and social practices (Giere 1988; Nersessian 2002) and the material and technological contexts (Pickering 1992) that characterise doing science. Niaz (2016), like Abd-El-Khalick (2012) and Lederman *et al.* (2002) claims that despite the complexity of multifaceted NoS issues and the controversy among philosophers of science themselves “a certain degree of consensus has been achieved within the science education community [such that] the nature of science can be characterised, among others, by the following aspects summarised in Table 3.

2.9.1. Experimentation and Empirical Nature of Science

Scientific knowledge relies heavily, but not entirely, on observations, experimental evidence, rational arguments, and scepticism (Arino de la Rubia, Lin, & Tsai, 2014; Duschl & Grandy, 2013). For a science knowledge claim to pass from the personal domain to the realm of shared scientific knowledge, the quality of the claim (*i.e.* the reliability and validity of the consolidated result) has to be considered and communicated (Tytler, Duggan, & Gott, 2001). Understanding the relationship between experimental data and scientific evidence is fundamental to one’s views of how scientific knowledge is generated (Buffler, Lubben, & Ibrahim, 2009). However, scientific knowledge is not exclusively determined empirically (McComas, 2002).

History of science shows that scientists do experiments and collect data, guided by their presuppositions (Niaz & Maza, 2011). However, they do not have direct access to most natural phenomena. Not every scientific discipline enables scientists to conduct experiments such as astronomy or not all scientific knowledge is

Table 3. Aspects and features of science relevant in the laboratory

NoS aspects	Explanation
Experimentation and empirical NoS	Scientists use observations and experiments when appropriate to test the validity of their claims. Not every scientific discipline enables scientists to conduct experiments, such as astronomy, and not all scientific knowledge is constructed as a result of experiments, such as evolution theory.
Tentative NoS	Although scientific knowledge is durable, it changes with new data or reinterpretations of existing ones. This change might be a complete (e.g., phlogiston theory vs. oxygen theory) or partial change (e.g., atom theories).
Scientific theories and laws	Scientific theories and laws have different meanings and roles in science. Scientific laws are descriptive statements about the perceived relationships, regularities, patterns, and generalisations in nature (e.g., Boyle's law). On the other hand, scientific theories are the explanations for phenomena or laws (e.g., kinetic molecular theory).
Creativity and imagination of science	Logic by itself is not sufficient for science. Creativity and imagination are required during various phases of a scientific study, such as constructing hypotheses, designing different methods for observation and experiments, and final interpretation of data.
Theory-ladenness and philosophical subjectivity	When scientists develop questions, design investigations, and make observations and inferences, their previous knowledge, experiences, and expectations, and the theories and laws that they believe, unavoidably affect them.
Social and cultural embeddedness	Politics, religion, philosophy, economy, and moral values are some of the factors that influence deciding what and how science is conducted, interpreted, and developed. In addition, scientific knowledge is produced, presented, and evaluated in social contexts including groups of scientists and scientific organisations.
The myth of scientific method	There are several common scientific processes—such as forming hypotheses, observation, experimentation, interpretation, and hypothesis testing—but these processes do not have to follow a specified order (e.g., Darwin proposed the theory of evolution right after his observations in the Galapagos Islands without forming an a priori hypothesis).
Models and inference in science	Scientific knowledge consists of the inferences derived from observations. Observations are descriptive statements about phenomena obtained by using senses (e.g., sight and hearing) or some technological device (e.g., using a scale to measure mass). However, inferences are the interpretations of these observations (e.g., Rutherford's atom model).

constructed as a result of experiments such as evolution theory (Demirdöğen *et al.*, 2016). Observations of nature are always filtered through our perceptual apparatus and/or intricate instrumentation, interpreted from within elaborate theoretical frameworks, and almost always mediated by a host of assumptions that underlie the functioning of scientific instruments (Lederman *et al.*, 2002).

2.9.2. Tentative Nature of Scientific Knowledge

While scientific knowledge is robust and reliable, all scientific knowledge has the potential to change with either the introduction of new data or the examination of existing data from different perspectives (Bell, Mulvey, & Maeng, 2016). Science is not an inalterable and rigid body of ‘absolute truths.’ A critical appraisal of the history of science shows that scientists continually look for theories that provide greater explanatory power (Niaz & Maza, 2011). Scientific progress is characterised by competition among rival theories (Duschl & Grandy, 2013). All scientific knowledge is technically provisional – that is, in principle open to re-examination in the light of new information (Taber, 2017a).

This is seemingly an attempt to veer away from realist perspectives on the status of scientific knowledge while simultaneously acknowledging that successes in science cannot simply be explained by social constructivist conceptions of NoS (Abd-El-Khalick, 2012). Tsai (1999) categorised students’ science epistemological beliefs into empiricist and constructivists. The empiricists see scientific knowledge as unproblematic and providing the right answers that are discovered by objective gathering of experimental data, and believe that carefully accumulated evidence will establish infallible knowledge. Constructivists view scientific knowledge as problematic, invented, subjective, and tentative and revisionary (Vhurumuku, 2011).

However, Lunde *et al.* (2016) acknowledge that there is an extent to which scientific knowledge is ‘established’. They argue, if knowledge from research frontiers is commonly encountered in everyday life, it becomes relevant and important for students to distinguish between reliable ‘established science’ knowledge and tentative knowledge claims from research frontiers, and to understand their differences. This implies that it is essential to ensure that school science students acquire some knowledge about the process of science, whereby claims from research frontiers either disappear from the scientific field or become established as reliable knowledge.

2.9.3. Scientific Theories and Laws

In their review of chemistry textbooks, Niaz and Maza (2011) illustrate that according to the positivist/empiricist perspective of progress in science, successive

verifications of a theory facilitate its conversion into a law, or vice versa, a law can be elevated to the status of a theory. Most modern philosophers of science have questioned this hierarchical/dichotomous relationship between laws and theories (Giere 1999). Similarly, Abd-El-Khalick (2012) asserts, we need to be aware that science textbooks are populated with a host of explicitly stated and didactically taught falsehoods about NoS, such as that, “A scientific law is simply a fact of nature that is observed so often that it becomes accepted as truth”. Laws and theories serve different roles in science and hence theories do not become laws even with additional evidence (Duschl & Grandy, 2013). Scientific theories and laws have different meanings and roles in science. Scientific laws are the descriptive statements about the perceived relationships, regularities, patterns, and generalisations in nature (e.g., Boyle’s law). On the other hand, scientific theories are the explanations for phenomena or laws (e.g., kinetic molecular theory). In general, scientific progress is characterised by a series of theories or models (plausible explanations), which vary in the degree to which they explain/interpret/predict the experimental findings (Niaz & Maza, 2011).

According to Taber (2017a), students often think that theories are scientists’ guesses or hunches that they are waiting to prove by experiments. Yet actually theories are the very basis of scientific knowledge. They are far more than guesses, as they must be based on extensive evidence, but they are always open to being surpassed when new data or a new interpretation of existing data comes along (Taber, 2017a). On the other hand, scientists refer to laws as if they are universally applicable descriptions of aspects of nature – but usually on the basis of data collection that is limited. The essence of science is developing explanatory schemes that make sense of extensive volumes of data that have predictive value.

2.9.4. Creativity and Imagination in Science

Scientists are sceptic of both data and its interpretations. Understanding data is a complex and lengthy process and requires considerable amount of ingenuity and creativity on the part of the scientists. They even often resort to imagination and speculation (Duschl & Grandy, 2013) to develop ideas that might represent aspects of nature – ideas that they then test as best they can (Taber, 2017a). Creativity

permeates all aspects of scientific investigations (Bell *et al.*, 2016), from hypothesis generation to data interpretation.

Science relies on creative thought as well as logic. Logic is needed when testing out ideas, but first scientists have to come up with the ideas to test. It is naive to think that scientists can move directly from data to scientific knowledge, as data always have to be interpreted in terms of some conceptual scheme. That scheme is an imaginative construction of the human mind. Science proceeds through the complementary roles of creative (expansive, imaginative, divergent) and logical (rational, closed, linear) thought (Taber, 2017a).

The aspects of the creativity and the empirical and inferential NoS are similar, because students must understand that out-of-the-box thinking is required in science, including proposing novel questions, creating new ways to analyse and visualise data, and finding relationships between what is known and unknown (Schussler *et al.*, 2013).

2.9.5. Theory-ladenness and Philosophical Subjectivity

Scientists invariably have presuppositions and prior theoretical frameworks before they start collecting data. At times these prior beliefs are well formulated and resistant to change (Niaz & Maza, 2011). Philosophers of science have emphasised the importance of such frameworks in scientific progress and refer to them in the following terms: guiding assumptions (Laudan *et al.* 1988); presuppositions (Holton 1978); and hard-core or negative heuristic of a research (Lakatos 1970). All these background factors form a mindset that affects the problems scientists investigate and how they conduct their investigations, what they observe (and do not observe), and how they interpret their observations. This (sometimes collective) individuality or mindset accounts for the role of theory in the production of scientific knowledge. Contrary to common belief, science never starts with neutral observations (Popper, 1992). Observations (and investigations) are always motivated and guided by, and acquire meaning in reference to questions or problems, which are derived from certain theoretical perspectives (Lederman *et al.*, 2002).

Scientific knowledge is influenced by theory that acts as a lens through which questions are developed; investigations are designed; decisions are made about

what, when, and even where data should be collected; and results are interpreted (Bell *et al.*, 2016). History of science shows that alternative interpretation of experimental data is one of the most interesting facets of NoS. It is generally believed that progress in science is a product of experimental data that unambiguously lead to the formulation of scientific theories (Niaz & Maza, 2011). When a new hypothesis is proposed, researchers try to assess its credibility by discussing the new theory in light of accessible empirical evidence and the massive network of existing established knowledge (Lunde *et al.*, 2016).

Matthews (2012) concedes that this conception can be ambiguous: one can say both 'yes' and 'no'. First to acknowledge that some claim is theory-laden is not equivalent to saying it is subjective in the usual psychological meaning of the term. But the meaning being used by the Lederman group is simply ambiguous. For instance Lederman says that 'I am not advocating that scientists be subjective' (Lederman, 2004, p. 306). Here 'subjective' must be the everyday psychological sense of the term. But previously we have been dealing with, what one might call, 'philosophical subjectivity', as it has been stated that subjectivity is equivalent to theory-ladenness, and that 'subjectivity is unavoidable' (*ibid.*). Clearly all science is theory-laden, as Lederman rightly points out; but if so, then scientists have to be subjective (as in philosophical subjectivity), whether it is advocated or not advocated. But this is entirely different from psychological subjectivity. The entire history of modern science is an effort to take out, or minimise, the psychological subjectivity in measurement and explanation.

2.9.6. Social and Cultural Embeddedness

Ideally science is independent of culture, as it is intended to be an objective quest for discovering true knowledge of the natural world. However, scientific knowledge is theoretical, and so based on constructs humans have developed to best describe and explain observations and measurements of nature (Taber, 2017a). Scientific ideas are affected by their social and historical culture (Duschl & Grandy, 2013). Politics, religion, philosophy, economy, and moral values are some of the factors which influence deciding what and how science is conducted, interpreted, and developed.

Kuhn (1962) suggested that different theoretical frameworks, with their different ways of seeing the world, were incommensurable (could not be measured against each other). He meant it was difficult to evaluate different frameworks objectively, as the evaluator would always be working from within their own existing worldview. Kuhn thought that science could make progress towards knowledge that better represented the true nature of things: but that this process was difficult because scientists can never completely step outside of the assumptions inherent in their habitual ways of making sense of the world.

Correspondingly, the contemporary understanding of the nature of science holds that the majority of scientists' engagement is not individual efforts toward final theory acceptance, but communities of scientists striving for theory improvement and refinement (Duschl & Grandy, 2013). Established knowledge is a result of acceptance in the broad research milieu, and can be characterised as knowledge that no one considers productive to question further (Bingle & Gaskell, 1994). Together with the overarching aim of reaching consensus, social activities such as discussions, debates and controversies among researchers have been described as key components of science (Driver *et al.*, 1996). This way of describing science-in-the-making can contribute to a more nuanced picture of scientific knowledge and makes it possible to examine scientific knowledge on different epistemological levels (Lunde *et al.*, 2016).

2.9.7. The Myth of Scientific Method

Despite it being debunked by philosophers, historians, sociologists, and scientists alike (Bauer, 1994; Niaz, 2016), the myth of a universal, step-wise, prescriptive, scientific method continues to linger on in some form or another in science textbooks and laboratory manuals (Abd-El-Khalick *et al.* 2008). Students and teachers continue to believe that scientific knowledge is actually generated and validated through the use of *the* scientific method.

According to (Marchlewicz & Wink, 2011), dissatisfaction with the traditional scientific method model abounds. It includes an overall linear view of the scientific process that occurs step-by-step in a sequential order. It excludes any theoretical, cultural, or social aspect to the creation of scientific knowledge. In addition,

traditional presentations of scientific method omit any hint of the human imagination, creativity, or philosophical subjectivity that is found in the actual inquiry.

One well known philosopher of science, Paul Feyerabend (1988) argued that there is no such thing as *the* scientific method, but rather, scientists have to develop their own customised methods that will work in their own areas of research (Taber, 2017a). Taber further describes that an experiment ideally explores a phenomenon under laboratory conditions, whereby variables of interest can be manipulated and measured and the potential effects of confounding variables controlled by keeping values constant. However, this is a problematic simplification in at least two regards. For one thing, not all scientists do experiments as such. In some branches of science it may be impractical or unethical to undertake experiments. It is not possible to manipulate the conditions at the centre of stars, or compare how life develops on a planet under different starting conditions.

2.9.8. Models and Inference in Science

The ubiquity of models in the history and current practice of science is widely recognised (Matthews, 2012). It is difficult to think of science without models: the 'billiard ball', 'plum-pudding' and 'solar system' models of the atom, the electron orbit model for the periodic table, the 'lattice' model of salt structure, the fluid-flow model of electricity, the double-helix model of the chromosome. They are seen as cognitive tools situated between experiments and theories (Duschl & Grandy, 2013). In the past half-century historians and philosophers of science have devoted considerable time to documenting and understanding the role of models in science and social science. These studies have led scholars to examine model-related topics such as the nature of scientific theory, the status of hypothesis, the role of metaphor and analogy in scientific explanation, thought experiments in science, and the centrality of idealisation for the articulation, application and testing of models. Mary Hesse's (1953, 1961, 1966) and Rom Harré's (1960) publications were foundational for the contemporary tradition (realist and non-realist) of model-related research, with Hesse's *Models and Analogies in Science* (1966) being of particular importance. Philip Johnson-Laird's book *Mental Models* (1983) was, and still is, enormously

influential. He, and associates, provided an explanation for the ubiquity of models in science when they detailed how models were ubiquitous not just in science but in all mental life.

According to Lederman *et al.* (2002), students should be able to distinguish between observation and inference. Observations are descriptive statements about natural phenomena that are directly accessible to the senses (or extensions of the senses) and about which observers can reach consensus with relative ease. For example, objects released above ground level tend to fall to the ground. By contrast, inferences are statements about phenomena that are not directly accessible to the senses. For example, objects tend to fall to the ground because of gravity. The notion of gravity is inferential in the sense that it can be accessed and/or measured only through its manifestations or effects, such as the perturbations in predicted planetary orbits due to interplanetary attractions, and the bending of light coming from the stars as its rays pass through the sun's gravitational field. An understanding of the crucial distinction between observation and inference is a precursor to making sense of a multitude of inferential and theoretical entities and terms that inhabit the worlds of science. Examples of such entities include atoms, molecular orbitals, species, genes, photons, magnetic fields, and gravitational forces (Hull, 1998, p. 146).

2.10. Pedagogical Goals and Frameworks for NoS in the Laboratory

An appropriate pedagogical framework is needed when conducting research on NoS, as it serves as a foundation on which the rationales are justified and theory revisited. It is also an effective tool to translate the somewhat abstract and philosophical notion of NoS into teaching practice. The literature clearly suggests that research on NoS falls within the domain of philosophy of science, often indicated by reference to the ontological and epistemological arguments for scientific theory (Aikenhead, 1987; Hodson, 1985; Kang & Wallace, 2004). It also draws frameworks from psychology, such as Nersessian's (1989) study on the comparative reasoning required in discovery and learning processes, which he found to be the same. A range of different pedagogical frameworks have been used to put the empirical research into perspective.

Yacoubian and BouJaoude (2010) found that science education researchers have focussed on at least two approaches to integrate NoS in science curricula. The first approach relies on the abstraction and teaching of certain general, universal aspects of NoS on which there is some consensus among philosophers of science. Abd-El-Khalick *et al.* (1998) argued that the philosophical disagreements are often irrelevant to K-12 students and suggested certain universal aspects of science that could be addressed in the science classroom, such as understanding that scientific knowledge is tentative, subjective, empirical, culturally and socially embedded, and a product of human creativity, imagination, and inference. The second approach relies on the practice of science itself, where diverse practices in different scientific disciplines when incorporated in science curricula might allow students to experience the diversity of the enterprise. Advocates of this approach criticise the first one as simplifying the workings of science for the purposes of instruction thus “shedding little light on the specifics of what scientists do” (Rudolph, 2000; p. 406) and considering changing the naïve views of NoS a straightforward task (Jenkins, 1996).

Abd-El-Khalick and Lederman (2000) categorises NoS pedagogies into two groups, *i.e.* implicit and explicit pedagogies. Implicit attempts utilised science process-skills instruction or engagement in science-based inquiry activities to improve conceptions of NoS. To achieve the same goal, explicit attempts used instruction geared towards various aspects of NoS and/or instruction that utilised elements from history and philosophy of science.

In the last six decades, research in the nature of science has utilised various pedagogical frameworks. Through a systematic review, I have synthesised such frameworks in the context of laboratory and the corresponding science education (classroom-based), as illustrated in Figure 12.

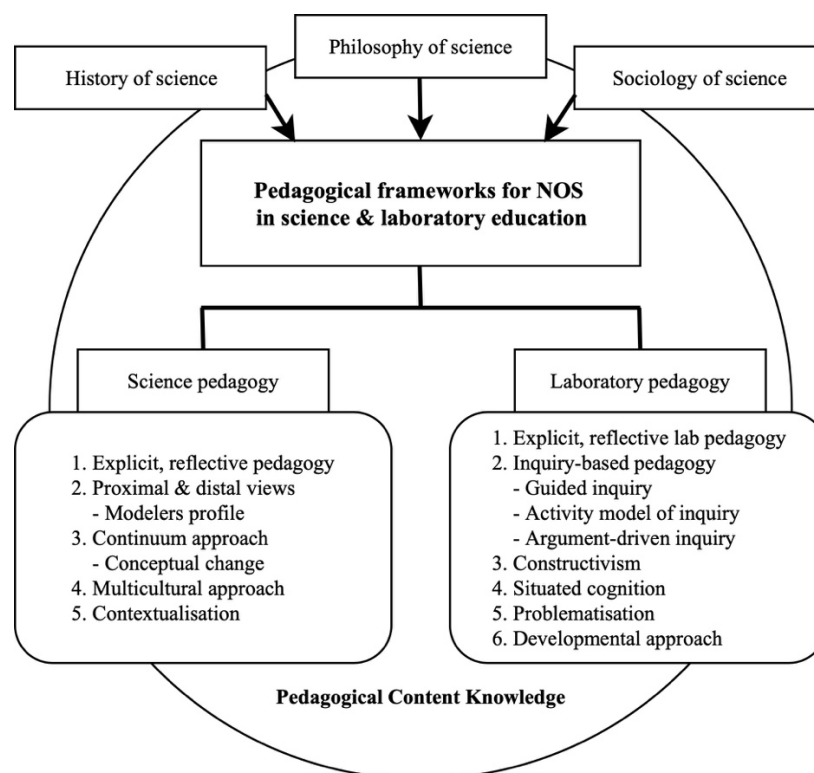


Figure 12. Various pedagogical frameworks used in research on NoS

As an integral part of science education, the laboratory has a distinctive pedagogy that characterises learning in its premises. Laboratory education is in itself a specific area of research on which the corpus of literature is growing. We have reviewed four decades of literature in laboratory education elsewhere (Agustian & Seery, 2017). We have also proposed a pedagogical framework to support learning in the complex learning environment in laboratory by scaffolding and providing information in advance of a complex learning scenario. We reassert the paramount importance of designing pre-laboratory activities that (1) are embedded into the overall laboratory learning process; (2) focus on the whole task, overall strategy and approaches; (3) provide supportive information; and (4) address the affective domain. The guidelines were intended to be applicable to any type of strategy for effective learning in the laboratory.

Akin to this context, the notion of NoS is heralded as one of the goals of laboratory education (Bates, 1978; Russell & Weaver, 2011). The literature suggests three different pedagogical approaches to NoS instruction in the laboratory, *i.e.* constructivism (Eymur, 2018; Ozgelen, 2012; Vhurumuku, 2011), guided inquiry (Martin-Dunlop, 2013), and situated cognition (Russell, 2011). According to

Vhurumuku (2011), the constructivist view of science entails an understanding that scientific knowledge is partly subjective, tentative, problematic, invented, and revisionary. Pomeroy (1993) categorises this view as non-traditional, as opposed to the traditional, largely positivist view. NoS instruction can also be approached from guided inquiry, whereby NoS is instructed in its authentic science learning environment. Martin-Dunlop (2013) found correlations between a favourable learning environment and improved understandings of NoS. Open-endedness and cooperation were identified as variables that contribute most, particularly the aspects of creativity and testability in science. Finally, situated cognition has been used as a pedagogical framework to facilitate NoS instruction (Russell & Weaver, 2011). It emphasises the importance of context in student learning, including the social, physical, and cultural contexts of a learning environment. Of three different laboratory curricula being investigated (traditional verification, inquiry-based, and research-based), they found that students in the research-based laboratory curriculum developed more sophisticated conceptions of NoS, more often than the other curricula.

2.10.1. Explicit, Reflective Pedagogy

One particularly promising method for teaching NoS involves an explicit and reflective approach (Williams & Rudge, 2016). Explicit in this case refers to planned instructional practices that allow for NoS aspects to be openly covered in class, whereas reflective refers to students having the opportunity to come to their own conclusions about NoS aspects and not just repeating what the instructor tells them. Explicit approaches consider the NoS understandings as cognitive instructional outcomes and the goal of improving students' NoS views can be planned accordingly (Yacoubian & BouJaoude, 2010).

Much research has shown that an explicit approach is more effective than implicit approaches in changing students' and teachers' views towards a more informed view of NoS (Bell, Lederman, & Abd-El-Khalick, 2000; Colagrande *et al.*, 2017; Goff *et al.*, 2012; Kang & Wallace, 2005; Mulvey & Bell, 2017; Schwartz *et al.*, 2004; Vesterinen & Aksela, 2012). Implicit approaches assume that NoS aspects will be learned as a by-product of doing science activities, whereas explicit approaches

include structured opportunities or prompts to help learners reflect on their science-based activities.

According to Goff *et al.* (2012), common wisdom presupposed that if students “did” science enough (in a classroom context), they would come to know NoS (Schwartz, Lederman, and Crawford 2004). Research indicates that an implicit approach is insufficient in the classroom, and is also inadequate to promote cogitative change regarding NoS in undergraduate research experiences as well (Lederman 1992). The relative ineffectiveness of the implicit approach could be attributed to two inherent assumptions. The first is that developing an understanding of NoS is an ‘affective’, as compared to a ‘cognitive’, learning outcome. The second ensuing assumption is that learners would necessarily develop understandings of NoS as a by-product of engaging in science-related activities.

ER pedagogy has to make not only NoS aspects explicit to students, but also meaning making explicit to instructors. These are skills critical to fostering classroom learning about any topic, and particularly for students to effectively learn about NoS using an ER pedagogical approach (Bautista, Schussler, & Rybczynski, 2014).

Reflective perspective on NoS entails that engaging learners with authentic scientific practice and inquiry activities provides the ideal context for influencing and assessing their NoS views. However, while necessary, this engagement is not sufficient. Engagement needs to be coupled with reflection (Abd-El-Khalick, 2012). An explicit-reflective approach to NoS instruction should not be equated or confused with didactic instruction. The label “explicit” is curricular in nature, while the label “reflective” has instructional implications.

Science education researchers have incorporated reflective elements in their attempts to teach NoS explicitly to middle school students (Carey *et al.*, 1989; Khishfe & Abd-El-Khalick, 2002) and found these elements effective in enhancing students’ views. The significance of incorporating reflective elements in teaching NoS lies in making learning more meaningful and effective (Yacoubian & BouJaoude, 2010). Reflective group discussions contribute to students’ learning from each other, thus making NoS instruction even more explicit. Researchers claimed that involvement in authentic science activities is not sufficient for students to develop representations of authentic science; students need to perceive them as important. In this regard,

learning in an inquiry-based laboratory is more efficient and meaningful if students are encouraged to engage in reflective discussions on their experiences. Reflective discussion by students on their findings is a crucial ingredient for meaningful learning in the laboratory (Yacoubian & BouJaoude, 2010).

Duschl and Grandy (2013) further distinguish the explicit-reflective (ER) pedagogical framework into two views. At the core of the debate is what comes to be seen as 'explicit' teaching of NoS. Version 1 advocates that teachers explicitly link the consensus statements to features of science lessons and activities. Version 2 advocates students engage in domain-specific scientific practices during weeks or months long curriculum units that focus the learners' attention on model building and refining enactments found in measuring, observing, arguing from evidence and explaining that are part of the growth of scientific knowledge.

Version 1 is grounded in the rational reconstruction philosophy of science that emerged as a response to Thomas Kuhn's historical-turn in *Structures*. An examination of the positions developed (i.e., separation of inquiry and NoS) by and of the philosophical references found in Abd-El-Khalick (2012) and Schwartz *et al.* (2012) supports our interpretation. Central to these historical turn philosophers and historians is a defence of science as a rational and objective way of knowing.

Version 2 we see as grounded in the 'Naturalised View of Philosophy of Science' that emerged among philosophers of science as another response to the historical turn. Version 2 is the more psychologically, philosophically, and pedagogically sound approach for teaching science and teaching about science. We believe students should learn through experience what it means to be rational and objective, and not to simply accept those adjectives as descriptors of science. The key element, obvious in retrospect, is that science is done by scientists and scientists are humans. The fundamental point is that humans are capable of constructing elaborate and powerful theories and technologies and understanding these capabilities involves understanding human invention and use of instruments, technical languages, social structures and learning environments. Two of the new elements in our understanding are an appreciation for the developmental sequence of human cognition and the multifarious value of models. The value of models, aids to cognition that give useful approximate representations were totally missing from the logical positivist picture

and mostly omitted from the writers in the historical turn. The third new feature is that doing science is situated in complex settings of cognitive, epistemic and social practices.

Naturalised philosophy of science views of science and science learning is fundamentally an enterprise of model building and refining, models being seen as cognitive tools situated between experiments and theories (Giere 1988, 2002; Nersessian 2002, 2008a, b). Version 2 sees inquiry and NoS as coupled.

2.10.2. Inquiry-based Pedagogy

Inquiry, with its structure and emphasis on thinking and working like a scientist, has become a signature pedagogy of science education (Crippen, Archambault, & Kern, 2013; Shulman, 2005). Internationally, scholars have called for more open-ended inquiry as an opportunity for students to gain a better understanding of the nature of authentic scientific work. Hodson (1996a) views “doing science” as a major aspect of science education and suggests that the focus of laboratory instruction needs to be placed on inquiry rather than learning specific scientific methods or particular laboratory techniques. Hofstein and Lunetta (2003) also emphasise the importance of inquiry as a major goal of laboratory instruction and argue that laboratory experiences may help students develop ideas about the nature of a scientific community and NoS.

Based on the importance of the process of science and related scientific practices, Lunde *et al.* (2016) define inquiry-based science teaching (IBST) as any activity that models (and thus mirrors) the epistemic characteristics of science as a collection of methods. That is, science as a collection of argumentative research communities; and science as part of society with the purpose to teach about nature of science as science-in-process. Lunde and colleagues argue that in order to obtain an adequate epistemological picture of scientific practices through laboratory work, students must have the opportunity to conduct open-ended inquiries while still receiving guidance concerning what should be investigated and how to carry out the investigations. According to NRC (2000), the essential features of inquiry include:

- Learners are engaged by scientifically oriented questions;

- Learners give priority to evidence, which allows them to develop and evaluate explanations that address scientifically oriented questions;
- Learners formulate explanations from evidence to address scientifically oriented questions;
- Learners evaluate their explanations in light of alternative explanations, particularly those reflecting scientific understanding; and
- Learners communicate and justify their proposed explanations.

Generally, the more closed the laboratory experiences the lower the level of inquiry, and the more open-ended the higher the level of inquiry (Vhurumuku, 2011).

A few studies on NoS in an inquiry-based laboratory context have been conducted (Lunde *et al.*, 2016; Marchlewicz & Wink, 2011; Ozgelen, Yilmaz-Tuzun, & Hanuscin, 2013; Schussler *et al.*, 2013; Yacoubian & BouJaoude, 2010). Marchlewicz and Wink (2011) adopt the activity model of inquiry as a theoretically grounded and empirically derived model of scientific inquiry to be used as a thinking frame to help students develop more informed views of NoS (see Figure 13). They argue that placing the features of scientific inquiry at the centre of a thinking frame may help students to better understand the process of science. The activity model of inquiry is considered relevant for use to develop students' understanding of the actual NoS as described in the work of Lederman. In particular, the lack of a linear structure, the focus on inquiry processes, and the inclusion of societal and cultural factors mean that scientific methods are presented by the activity model of inquiry as variable, open-ended activities. The model implicitly includes some of the aspects of NoS. From the model's many intersecting lines (Figure 13), it can be seen that there are countless ways to approach an inquiry, and the assignments can be used as guides for students to see how they approach their own scientific problem solving.

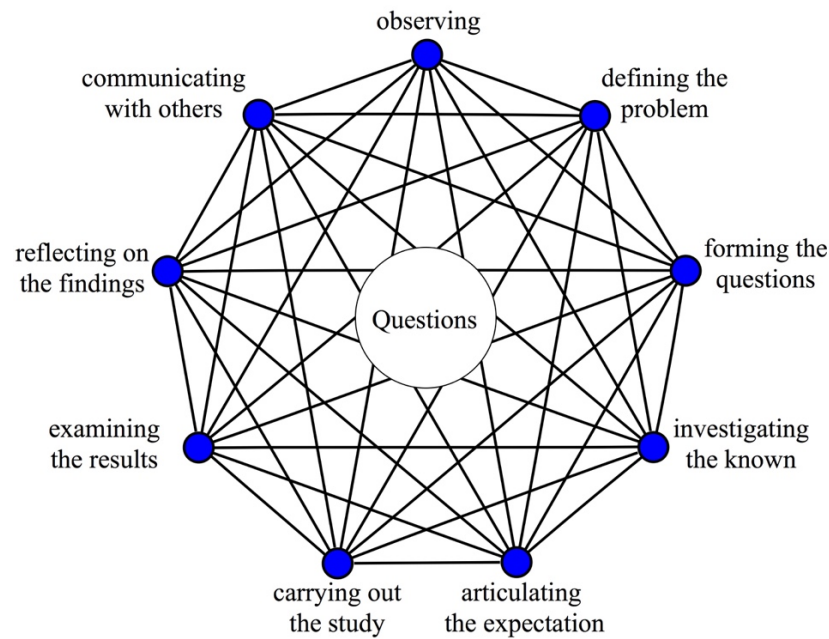


Figure 13. Activity model of inquiry (Harwood, 2004)

Conducted from a slightly different perspective, Yacoubian and BouJaoude (2010) used guided-inquiry approach to investigate the effect of explicit, reflective pedagogy on student's views of NoS. During each class session, students worked in groups of two for 50 minutes on the laboratory activity. Following the laboratory activity, students in the experimental group (exposed to ER pedagogy) individually answered open-ended questions about NoS for 20 minutes and then engaged in a reflective discussion with their peers about NoS for 20 minutes. The teacher guided the discussions by asking the students reflective questions with an attempt to make aspects of NoS explicit. They found that there seemed to be five major challenges that students faced in their attempts to change their NoS views:

- viewing science as a relative enterprise
- differentiating among the components of inquiry
- realising the possibility of different explanations for the same phenomenon
- viewing scientific experiments as tools rather than goals of science and viewing communication as a tool in the construction of scientific knowledge
- understanding the relation between personal learning of science and construction of scientific knowledge.

The intervention in their study corresponded to level 1 on the Herron Scale, in which the problem and procedure are provided and students have to look for the

solution (Herron, 1971) and thus could be considered as guided rather than open-ended inquiry activities (Yacoubian & BouJaoude, 2010). Herron describes four levels of inquiry which are confirmatory, structured, guided, and open. The scale provides a framework of thinking in which the higher the level the less will be the guidance provided to students when engaged in inquiry-based activities. The guided inquiry approach developed by Eggen and Kauchak (1996) allows students to experiment and at the same time engage in reasoning in order to arrive at a particular scientific rule or principle. Crippen *et al.* (2013) make a case for finding a nuance in the spectrum of closed- and open-ended inquiry. They argue, in order to obtain an adequate epistemological picture of scientific practices through laboratory work, students must have the opportunity to conduct open-ended inquiries while still receiving guidance concerning what should be investigated and how to carry out the investigations.

2.11. Summary

In this chapter, two distinctive lines of research have been reviewed, *viz.* undergraduate chemistry laboratory education and the nature of science. In the first part, I have argued for laboratory education by revisiting its role and situating it in relevant curricula and pedagogical frameworks. I have also summarised a review of research in pre-laboratory activities published as a part of this study, and restate the importance of effective feedback and assessment. In the second part, I have reviewed the contemporary views on the nature of science and argued for its teaching in the laboratory. The term has been redefined for the context of laboratory education and several relevant NoS aspects have been elaborated. Lastly, I have set teaching and learning goals for NoS in the laboratory and recommended relevant pedagogical frameworks. Following this is a chapter on methodology, where the key issues reviewed in the literature will be juxtaposed with the research problems stated in the preceding chapter to determine the strategies and methods of inquiry.

Chapter Three. Methodology

In this chapter, I will argue for and against several methodological alternatives relevant to the problems being investigated. In doing so, the main research questions formulated in sections 1.6.1 and 1.6.2 will guide the deliberation with regards to methodology, methods and instruments. These questions are:

- What are characteristics of students' meaningful learning experience in the undergraduate chemistry laboratory in relation to the pre-laboratory activities?
- To what extent do students understand the nature of science in the context of the undergraduate chemistry laboratory?

This research project is situated in the intersection between the practice and research of science education and a host of other well-established fields of scholarship, *i.e.* history and philosophy of science, cognitive psychology, sociology, and the overarching educational research, as visualised in Figure 14. Due to the interdisciplinary nature of this study, the methodology and methods chosen to investigate the research questions formulated in Chapter One are derived from theoretical and philosophical frameworks that inform the various elements of the research issues at hand, as previously elaborated in sections 2.3 and 2.10.

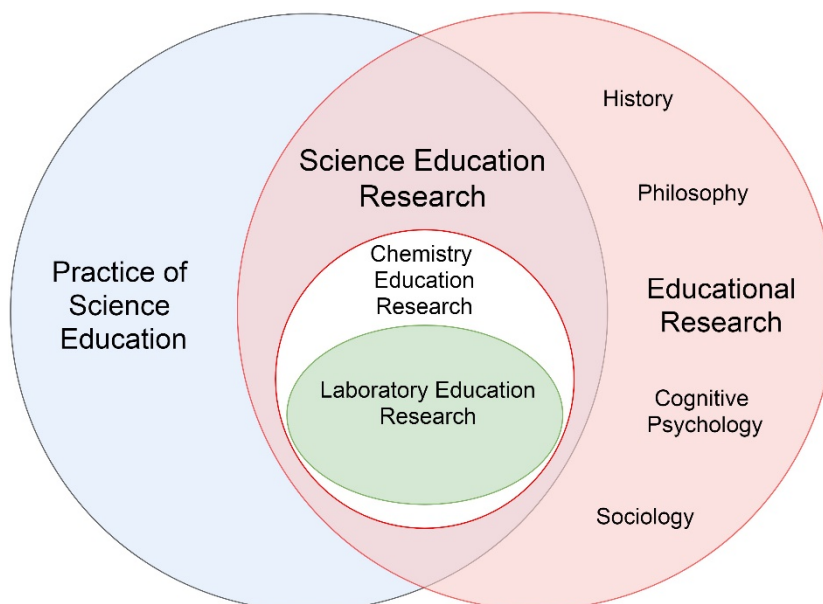


Figure 14. Laboratory education research in the intersection of research and practice

3.1. Mixed Methods Paradigm

In order to inquire into the research problems, a mixed methods research paradigm was used, in which both quantitative and qualitative methods are integrated. This paradigm is argued to provide a better understanding of the problem than either quantitative or qualitative data in isolation, by means of alternative perspectives and condensed as well as detailed description (Creswell, 2012). Greene and Caracelli (1997) speak of a dialectical position, whereby multiple worldviews are honoured. Accordingly, Greene, Caracelli, and Graham (1989) argue that a mixed methods paradigm provides a sound platform for:

- triangulation, whereby validity is increased and bias minimised;
- complementarity, whereby the strength and weakness of individual methods complement each other;
- development, whereby the results of one method are used to enhance another;
- initiation, whereby data analysis provides avenues for different perspectives; and
- expansion, whereby the scope of research is increased.

In a mixed methods paradigm, different priorities can be weighed between an emphasis on qualitative or quantitative data (Molina-Azorin, 2016). Correspondingly, the implementation of data collection can also follow a particular sequence. In this study, the qualitative element was emphasised, on the rationale of research questions and the issues investigated. Students' learning experience, as opposed to other terminologies such learning outcomes or learning results, is a concept that is arguably better verbalised than quantified. Likewise, students' views and understanding of the nature of science lend itself to a qualitative substantiation, rather than numerical data. That being said, there is some degree of importance to gauge an extent to which the undergraduate students in the context of this study make use of certain learning strategies, especially with regards to the pre-laboratory activities. In the following sections, relevant methodological issues will be discussed, the context of the study will be described, and research instruments and analyses will be elaborated.

3.2. Hermeneutic Phenomenology

The qualitative part of the data in this study is analysed through a hermeneutic phenomenology lens, which is an approach to exploring the conscious experience of phenomena from the viewpoint of individuals (Coles & McGrath, 2010). The father of phenomenology, Husserl (1970), states that phenomenology is more interested in the process of knowing and understanding, rather than finding hard, external reality. It questions the obvious and transforms it into something intelligible, through exploration, examination, elaboration, and explanation of meanings. Schutz (1967) maintains that in order to analyse those meanings, the world of experience (*Erfahrungswelt*) is contextualised as a total structure built with different arrangements and identifying characteristics.

In juxtaposition to the conventional chemistry research, a hermeneutic researcher uses a different approach to data, methods and theory from a researcher operating from within a positivist framework, which typifies a conventional chemical researcher. In hermeneutic research such as phenomenology, accounts of social reality held by the research participants are prioritised (Bunce & Cole, 2008; Scott & Usher, 1996). To some extent, this research gives them a voice. Intentionality and subjective meanings are valued as much as hard, numerical data.

Likewise, in comparison to other qualitative research approaches such as discourse analysis and grounded theory, phenomenology serves the purpose of understanding how students make meaning of their lived learning experience. This study does not seek to examine how language is used to accomplish personal, social, or political goals, which typifies a discourse analysis approach. Neither does it aim to develop explanatory theories of basic social processes studied in the context, which typifies a grounded theory approach.

Hermeneutic phenomenology has a potential as a research framework for discerning learning experiences in laboratory (Casey, 2007; Gatlin, 2009, 2014). It is because learning experiences encompass not only cognitive dimension, but also affective and conative. The complexity of psychological and educational domains is often dismissed by researchers operating in the hyperrational domain (Kincheloe & Berry, 2004). They further argue that human beings do not act in automatic response

to physical forces such as atmospheric pressure. Rather, they move within intentional frames of mind that at times lead to unexpected or irrational behaviours. This phenomenological form of information is necessitated by particular epistemological and ontological conditions rarely recognised in monological forms of empirical research. Mayoh and Onwuegbuzie (2015) advocate mixed methods that incorporate phenomenology in order to describe or to interpret human experience as lived by the experienter in a way that can be used as a source of qualitative evidence, alongside the quantitative findings that can, to some extent, be more generalisable.

3.3. Context and Participants

The context of this study is the physical chemistry laboratory at the University of Edinburgh, which is a part of undergraduate physical chemistry course. The whole study was conducted from September 2016 until August 2019. The pilot project takes into account Year 3 students as participants.

3.3.1. Physical Chemistry Laboratory Course Description

The third-year physical chemistry laboratory course is aimed to give students further practical experience of techniques; help them develop the skills to design, plan and carry out their own experiments; teach them to critically appraise the validity of data and work to high professional standards of safety and practice; and further develop their scientific writing skills. In third year physical chemistry, students attend for 6 h a week with an assumption that they will spend 6 h a week on processing and analysis in preparation for their report.

In the course of three years that this research was conducted, there has been a structural change in the Year 3 physical chemistry laboratory curriculum, as described in Seery *et al.* (2018b). Prior to the change, students completed four expository experiments followed by two weeks of investigative inquiry, amounting to a total of six weeks of laboratory rotation. In the new structure, an expository experiment (labelled as Part 1), is immediately appended with an investigative inquiry based on Part 1 (labelled as Part 2), so that students have sufficient time to study the chemistry behind the experiments in more detail and gradually conduct more inquiry to prepare them for more advanced stages in their laboratory course.

3.3.2. Organisation of Laboratory Instruction

3.2.2.1. Pre-laboratory. The existing pre-laboratory resources at the physical chemistry laboratory are accessible on an electronic platform called eLM (electronic Lab Manual). Depending on the experiment, they usually consist of a pre-laboratory video on the underlying theory, a pre-laboratory video on relevant experimental skills, a post-laboratory video on data analysis, and an online discussion forum. A printed out laboratory manual is given as a reference, in which a few questions related to the experiment are to be answered and submitted prior to laboratory work.

3.2.2.2. Laboratory work. The experiments are designed to be completed within three hours. In the first part of the experiment, students complete a traditional expository experiment to familiarise with experimental techniques and types of data. In the following second part, they utilise these techniques in an inquiry-based experiment, with additional complexity of experimental design (Seery *et al.*, 2018). Usually students work in pairs. All reports are written and submitted individually. Demonstrators are within reach at all times for any queries regarding the experiment. Albeit they do not give brief pre-laboratory lecture, they play a role as a supervisor.

3.2.2.3. Post-laboratory. The class is divided into seven groups, each of which is formally assigned to two 3-hour sessions per week. The first session is for the experiment and the second is a write-up session. The write-up session is also supervised by demonstrators.

3.4. Ethical Considerations

Bryman (2008) argues that researchers must be aware of the issues involved in the research so as to make informed decisions about the implications of certain choices, particularly the issues that arise in relations between researchers and research participants. It is important to keep in mind that the ethical issues in the course of doing research are most likely to impinge on the participants as well as the researcher. Therefore, I followed the ethical principles in social research as proposed by Bryman (2008). I ensure that the research does not harm the participants to any extent, be it physically or psychologically. One way of going about it is by ensuring

data protection. I ensure that any data gathered from this study are confidential. When I have to use names, they will all be pseudonyms. The interviews were transcribed in a way that no participants or schools can be identified. The other ethical issue that I address here is the informed consent.

Christians (2005) states that participants must agree voluntarily to participate in the research, without physical or psychological coercion. In my study, I ensure that the participants had all the information with regard to the research before they gave consent. Before proceeding to observation and interviews, I asked them to read the participant statement and decide whether they wish to participate or not. They were informed that they could withdraw from the study at any time without affecting the relationship between them and the institutions which were involved in the study.

3.5. Validity and Reliability

Babbie (2010) concedes that the measures of research drawn from qualitative research are often criticised as superficial and not really valid. As compared to surveys and experiments, the kinds of comprehensive measurements available to the qualitative researcher tap a depth of meaning in concepts. Instead of specifying concepts in quantified measures, a qualitative researcher commonly gives detailed illustrations. According to Denscombe (2010), the issue of validity may really have to be addressed in qualitative research. It is difficult, for example, to check whether information given by the participants is honest or of a factual nature. However, Denscombe suggests that the researcher should gauge the credibility of what the participants have said and avoid being a 'gullible dupe' who accepts anything without being critical.

Likewise, Babbie (2010) also advises that qualitative research can pose problems of reliability. Although they are in-depth, the measurements are also often very personal. Thus, apparently valid findings from a research might not be replicable in a different setting, even with the same amount of research instrumentations. Babbie suggests that qualitative researchers should be conscious of this issue and take pains to address it. One way of addressing this issue is through comparative evaluations, which might entail two different settings to compare. In this study, a way

of addressing the issue of reliability is the multiple cycles of data collection and triangulation of various research instruments.

Robson (2002) observes that a phenomenological case study might just be concerned with explaining and understanding what is going on in a particular setting, hence external generalisability may not be an issue. Cohen *e.a.* (2007) assert, though, that generalisation in case study must be clarified. In this light, Bassey (2002) suggests that the use of fuzzy generalisation for qualitative study serves as the most reasonable way of projecting the study of singularity onto similar situations elsewhere. As opposed to statistical generalisation in quantitative study and empirical generalisation in scientific research, fuzzy generalisation will be a way of tackling this issue. Also, Misco (2007) speaks of an alternative to generalisability, *viz.* transferability.

The findings from this research will be characteristic of the particular research setting in which this study has been conducted, but drawing from the similarity of the type of laboratory, curricula, as well as underlying philosophy of the undergraduate chemistry education, this study will be likely to have common features of students' learning experience and their views of science. Evidently, some lessons will definitely be learnt to inform my own professional development as a science education researcher and practitioner.

3.6. Reflective Practice

I firmly advocate reflective practice in this research, as it is one of the central strategic themes of contemporary, postmodern qualitative inquiry (Patton, 2002). Hence, reflection and reflexivity are embodied in the study. According to Bolton (2010), reflection and reflexivity entails contestation, questioning the status quo and the taken-for-granted. The process goes on through constructive developmental change which illuminates the existing knowledge.

In this study, I advocate reflective practice as proposed by Bolton (2010), who defines reflective practice as:

[a creative process of] learning and developing through examining what we think happened on any occasion, and how we think others perceived the event and us, opening our practice to scrutiny by others, and studying texts from the wider sphere'. (Bolton, 2010: 7)

Furthermore, Bolton asserts that reflexivity is the way of discovering strategies to observe those experiences as an inquiry. It involves an awareness of the way one is experienced and perceived by others. It is a higher level of reflection in which we reflect on our reflection. Patton (2002) emphasises the importance of reflexivity, which entails voice and perspective, in doing research. The notion of self-awareness, political and cultural consciousness, and ownership of one's perspective are crucial to the significance and relevance of the research. Reflexivity reminds me to observe myself so as to be attentive to and conscious of the cultural, political, social, linguistic, and ideological origins of my own perspective and voice as well as the perspectives and voices of those I observe and talk to during the data collection. There is potential contradiction or perhaps confirmation of what I perceive and understand.

In an attempt to translate an abstract concept of reflection into a concrete model, I adopt the three- stage model of reflective learning proposed by Scanlan and Chernomas (1997) as seen in Figure 15. I refer to the word learning because I intend to really learn from and make the most out of the research that I have conducted. The findings of this study should inform and illuminate my own practice.

In Scanlan and Chernomas's model, the first stage of reflection is awareness, stimulated by some uncomfortable, disturbing thoughts or feelings or even positive thoughts or feelings about a learning situation or event. The second stage is critical analysis, in which the individual critically analyses the situation, taking into account their relevant knowledge and experience as well as the application of new knowledge resulting from the analysis process. The third stage of the model is learning, which involves the development of a new perspective based on the critical analysis and the application of new knowledge to the learning situation under reflection. Loo and Thorpe (2002) describe these three stages in a way that they are connected chronologically from the past to the future.

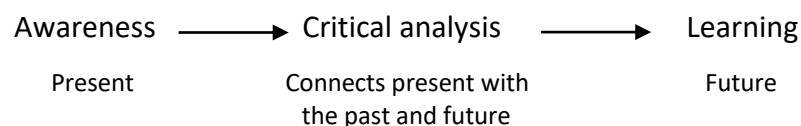


Figure 15. Scanlan and Chernomas's (1997) three-stage model of reflective process

3.7. Research Instruments and Measures

As argued in the beginning of this chapter, this study incorporates both qualitative and quantitative research instruments. In deciding which instruments and measures to use, the research questions serve as a frame of reference. For example, the first main research question *“What are characteristics of students’ meaningful learning experience in the undergraduate chemistry laboratory in relation to the pre-laboratory activities?”* was addressed with semi-structured interviews following a laboratory exercise, student questionnaires on laboratory learning, and observations in the laboratory. In the following subsections, these instruments will be elaborated.

3.7.1. Semi-structured Student Interviews

Students were interviewed on their cognitive and affective experience in the laboratory. The semi-structured interviews consist of several questions on elaboration of the statements in the student questionnaire on laboratory learning (see Subsection 3.7.2), as well as additional questions derived from DeKorver and Towns (2016). Questions such as ‘How did you manage the amount of information during the experiment?’ and ‘What do you think about the chemistry behind the experiment you have done?’ are asked to explore their cognitive experience. The interviews also probed into their affective experience, through a question such as ‘How were you feeling when you were doing the experiment?’ The interview protocol is appended in this thesis (Appendix 7.3).

3.7.2. Student Questionnaire on Learning in the Laboratory

In order to gauge students’ responses on several aspects of laboratory preparation and learning, a 5-point Likert scale questionnaire was designed for this study. There are 24 statements about pre-laboratory preparation, pre-laboratory videos, the experiment, and some post-laboratory aspects. They were formulated based on previously validated questionnaires and literature reference on learning in laboratory and chemistry at large. Lastusaari, Laakkonen, and Murtonen (2016) validated the ChemApproach questionnaire to assess students’ approaches to learning in chemistry, according to the depth of learning and the extent to which

students actively learn. Four of the 17 statements in their questionnaire are about laboratory work.

The questionnaire also refers to Tuan *et al.* (2005) on students' motivation towards science learning and Dalgety, Coll, and Jones (2003) on attitudes and experiences in chemistry learning. Aside from these validated questionnaires, the literature on pedagogical approach to laboratory and philosophical underpinning of laboratory work, as argued in the previous chapter, also inform the statements chosen in this study (Cleminson, 1990; Sweller & Chandler, 1991).

3.7.3. Meaningful Learning in Laboratory Inventory

In the next phase of research, the validated Meaningful Learning in Laboratory Inventory (MLLI) was administered in order to gauge students' expectations in the laboratory from cognitive and affective viewpoints. The MLLI questionnaire was developed and validated by (Galloway & Bretz, 2015a, 2015b) as an assessment tool to measure students' perspectives of learning whereby both cognitive and affective domains are integrated into the psychomotor domain of doing experiments in the laboratory. The 31-item questionnaire consists of statements about students' expectations of laboratory courses.

3.7.4. Views of Nature of Science

The evaluation instrument Views of Nature of Science (VNoS) was developed by Lederman's research group (Bell *et al.*, 2003; Lederman *et al.*, 2002; Schwartz *et al.*, 2004). It was designed mainly on a rationale that previous convergent instruments were all based on forced-choice items such as Likert-scale, agreement/disagreement, or multiple choice. See for example, Billeh and Hasan (1975), Cooley and Klopfer (1961), and Rubba and Andersen (1978). Resulting in three forms, VNoS development addressed issues regarding validity and the usefulness of previous instruments, as well as developers' biases related to their NoS views.

In this study, an adapted version of VNoS Form B was used to evaluate undergraduate students' views of the nature of science in the laboratory. The instrument consists of seven open-ended statements that correspond with seven aspects of the nature of science, *i.e.* empirical nature of scientific knowledge,

inference and observation in science, tentative nature of scientific knowledge, scientific theories and laws, creativity and imagination in science, philosophical subjectivity in science, and social and cultural embeddedness of science. A redefinition of these aspects in light of the current philosophical debate has been argued elsewhere (Agustian, 2019).

3.8. Data Collection

During the data collection, I took the role as an overt researcher, which entails that I revealed my identity as a researcher to my participants. Potential bias was reduced by the fact that I was not taking up a position as demonstrator at the physical chemistry laboratory. Students were given all the opportunity to be honest and straightforward about their response, be it in the quantitative or qualitative data collection.

Quantitative research instruments (the student questionnaire on learning in the laboratory and Meaningful Learning in the Laboratory inventory) were administered during laboratory periods. Considering time constraints, the instruments were designed (or modified) so that students were able to complete and return them whilst having enough time to finish their experiments. Students were also observed within these time limits. Additional information was gathered from demonstrators and laboratory technicians as well.

Through the course organiser, emails were distributed regarding invitations for participating in the interviews. All interviews were conducted out of laboratory periods, but still within the premise of the College of Science and Engineering. Due to the entirely voluntary nature of participation in this research, no attempt was made to reach a particular proportion of participants, either in terms of gender, national, or linguistic background. In the invitation email, it was emphasised that this study was conducted and contextualised in their laboratory, with a purpose of improving their laboratory learning experience.

3.9. Data Analysis

3.9.1. Phenomenological Analysis

Following up an email regarding a request for participation in this study, eight students in Phase 1 and six students in Phase 2 responded and stated they were willing to be interviewed, each receiving an Amazon voucher incentive (of £10 value) as an acknowledgement of their dedicated time. The interviews were recorded, upon their informed consent. The recording was then transcribed verbatim and coded for emerging themes.

Subsequently, the qualitative data was analysed according to well-established phenomenological analysis strategies (Priest, 2002). The data were organised and analysed according to the Stevick-Colaizzi-Keen method (Moustakas, 1994). Departing from the verbatim transcript, the following steps were completed:

- Carefully weighing each statement with regards to significance for description of learning around the laboratory
- Recording all relevant statements
- Organising nonrepetitive, nonoverlapping statements into so-called invariant horizons or meaning units
- Clustering the invariant horizons into themes
- Synthesising the invariant horizons and themes into *a description of the textures of the experience*, whereby verbatim excerpts were included
- Constructing *a description of the structures of researcher's experience* by reflecting on researcher's own textural description
- Combining the *textural and structural descriptions* of the meanings and essences as perceived by the researcher

An example of how this was conducted is appended to this thesis (7.4 Appendix F).

3.9.2. Coding

The qualitative data from the first round of data collection (Phase 1) were coded initially according to the categorisation of the interview questions. This immediately expanded as new themes emerged from the data. Concurrently, some initial codes were altered, combined, or omitted. From Phase 1, the following themes emerged from the data:

- Pre-laboratory work
 - Personal goals
 - Preparing for laboratory
 - Pre-lab aspects effective for learning
 - Pre-lab videos
 - Lesson learnt and suggestions for modifications
- Information management
 - Relevant information vs noise
 - Chemistry behind the experiment
- Nature of science
 - Views of tentative nature of scientific knowledge
 - Arguments for NoS
 - Instructional features that may influence NoS views
 - Pre-laboratory work and NoS
- Affective domain
 - Emotional aspects during the experiment
 - Level of confidence
 - Challenges and motivation for learning

Additional codes such as demonstrator's role and post-laboratory aspects also emerged and were analysed. In this phase, the inquiry was focussed more on students' learning experience in the laboratory, particularly in relation to pre-laboratory activities and how they have been used. In Phase 2, the focus was almost entirely on students' understanding of the nature of science in the context of the physical chemistry laboratory. It is noteworthy that Phase 2 was conducted within the context of the new laboratory curriculum, as described in Subsection 3.3.1. Akin to the previous phase, initially the codes followed the interview protocol, which was based on the Views of NoS open-ended questionnaire. The following themes emerged:

- NoS in the laboratory
 - Physical chemistry laboratory
 - Organic chemistry laboratory

- Cookbook experiment
- Pre-laboratory work and NoS
- Views of NoS (all categorised into three levels: naïve, transitional, informed)
 - Experimentation and empirical NoS
 - Inference, observation, and theoretical entities in science
 - Tentative nature of scientific knowledge
 - Scientific theories vs scientific laws
 - Creativity and imagination in science
 - Philosophical subjectivity and theory-ladenness
 - Social and cultural embeddedness
- 2-part laboratory structure
 - Strategies to cope with challenges in the laboratory
 - Recommendations

3.9.3. Quantitative Analysis of Student Questionnaires

All in all, 48 students in the pilot phase returned the student questionnaire on learning in the laboratory, 51 students in Phase 1 returned the Meaningful Learning in the Laboratory Inventory (MLLI), and 30 students in Phase 2 returned the Views of Nature of Science open-ended questionnaire.

With regards to the student questionnaire, although the statements were valid for all experiments, with the exception of statements regarding pre-lab videos in the gas chromatography experiment due to the inexistence of the pre-lab videos, students were mainly asked to fill in the questionnaire with the flash photolysis experiment in mind. This experiment was chosen upon discussion with the laboratory organiser. Since the gas chromatography experiment did not come with pre-laboratory videos, several participants were also asked to fill in the questionnaire with regards to this experiment, and a comparison was made to the flash photolysis experiment. Data was then fed into Excel and number of responses was counted. The number of responses was chosen as opposed to statistical means on the rationale that the 5-point Likert scale has no equal intervals between the values.

The MLLI was designed with measures of 0 to 100 scale, allowing students to refine their responses. The authors of this inventory require that the instrument be

administered as it is. No modification or adjustment to the statements was made. However, in the analysis, these statements were categorised into cognitive, affective, and cognitive-affective domains. Also, the instrument was meant to be administered twice, before and after an intervention. However, because this study is non-interventionistic, it was administered once.

The Views of Nature of Science (VNoS) Form B was analysed according to an evaluation rubric (see Table 7). Responses were weighed against these criteria and they were marked according to the level of understanding. The number of students within each level was recorded and is reported in the next chapter.

3.10. Summary

In this chapter, I have elaborated on the methodology chosen for this study. A mixed methods paradigm encapsulates the entire study, with a deliberate emphasis on the qualitative element. Accordingly, the qualitative part of this research is informed by hermeneutic phenomenology. I have described the setting and sampling and argued for validity and reliability of the study, as well as reasserted the reflective practice espoused in the data analysis stage. Research instruments and measures have been specified and data collection and analysis have been described.

In the next two chapters, I will present results and discussions from the data analysis and interpretation. It will be organised as such. In Chapter Four, I will present findings and discussions related to the first part of the study, *i.e.* students' learning experience in the laboratory. This will be aligned with the issues discussed in the literature review and guided by the research questions. As previously stated, pre-laboratory work is emphasised. In Chapter Five, I will present findings and discussions related to the second part of the study, *i.e.* the nature of science in the context of the undergraduate chemistry laboratory. The redefinition of NoS and conceptualisation of its aspects will guide the interpretation of data.

Chapter Four. Students' Learning Experience in the Laboratory

In this chapter, I will present results and discussion of the first part of the study, concerning students' learning experience in the undergraduate chemistry laboratory. The research question that guides this part is *"What are characteristics of students' meaningful learning experience in the undergraduate chemistry laboratory in relation to the pre-laboratory activities?"* This question is further specified into three sub-questions. Firstly, the sub-question 1a *"What are ways in which students prepare for their laboratory work?"* was investigated by administering Student Questionnaire on Learning in the Laboratory (Appendix 7.1) and conducting semi-structured interviews (Appendix 7.3). Secondly, the sub-question 1b *"Which learning goals pertinent to the laboratory are prioritised by students?"* was resolved with Meaningful Learning in Laboratory Inventory (Galloway & Bretz, 2015a, 2015b) and semi-structured interviews. Lastly, the sub-questions 1c *"How do students manage information during their laboratory work, in relation to the pre-laboratory activities?"* and 1d *"To what extent does students' learning experience influence their affective domain?"* were resolved with semi-structured interviews. In addition, laboratory observations and conversations with laboratory demonstrators also provide extra information to supplement the findings substantiated through the interviews and questionnaires.

4.1. Students Questionnaire on Learning in the Laboratory

The student questionnaires were administered during laboratory sessions of Year 3 Physical Chemistry, initially focussing on a Flash Photolysis experiment. The responses were analysed using Excel and preliminary conclusions were drawn from the quantitative data. Due the non-interval nature of Likert scores, the number of responses were counted, while descriptive statistics were also provided.

Table 4 shows that in general, students feel that they are well-prepared for the flash photolysis experiment (median 4 for lab preparation). They strongly agree that pre-lab videos help them understand the experiment and reduce cognitive loads (median 5 for statements 6 and 12). Somehow they are indecisive about whether or

not the videos motivate them to learn more about the topic (median 3 for statement 11) or if they know how they can go about the questions they have upon watching the videos (statement 8), but the pre-lab videos have generally been useful to prepare them for the laboratory and the calculation needed to analyse the data.

It is interesting, perhaps also intriguing, that students agree on the statements related to the experiment (median 4), such as that they can understand the chemistry behind flash photolysis by doing the experiment, or that they are confident enough with the relevant laboratory techniques to be able to concentrate on the chemistry involved in the experiment. This section would need elaboration from interviews and triangulation from observation data.

Table 4. Likert scores & descriptive statistics of the flash photolysis experiment (n=33)

	Q#	Likert scores					Descriptive statistics		
		1	2	3	4	5	Mean	Median	SD
Preparation for lab	1	1	1	3	20	8	4	4	0.87
	2	1	1	10	16	5	3.7	4	0.88
	3	0	0	7	12	14	4.21	4	0.78
	4	1	6	2	8	16	3.97	4	1.26
	5	0	0	10	13	10	4	4	0.79
Prelab videos	6	1	1	0	12	19	4.42	5	0.9
	7	1	3	10	16	3	3.52	4	0.91
	8	0	3	15	12	3	3.45	3	0.79
	9	1	1	7	17	7	3.85	4	0.91
	10	1	1	13	14	4	3.58	4	0.87
	11	1	5	13	11	3	3.3	3	0.95
	12	1	2	3	10	17	4.21	5	1.05
The experiment	13	0	2	7	15	9	3.94	4	0.86
	14	0	3	7	15	8	3.85	4	0.91
	15	0	0	4	19	10	4.18	4	0.64
	16	0	0	6	17	10	4.12	4	0.7
	17	1	1	8	16	7	3.82	4	0.92
	18	0	1	10	15	7	3.85	4	0.8
	19	0	0	7	15	11	4.12	4	0.74
	20	0	3	5	14	11	4	4	0.94
After lab session	21	0	2	9	8	14	4.03	4	0.98
	22	0	1	8	16	8	3.94	4	0.79
	23	0	3	8	16	6	3.76	4	0.87
	24	1	0	3	18	11	4.15	4	0.83

Along with the data from the interviews and supplemented from laboratory observations and conversations with demonstrators, the quantitative data extracted from the student questionnaires are aimed at resolving the research questions formulated in section 1.6.1, particularly the sub-questions 1a and 1d. This will be discussed further in section 4.4.

4.2. Meaningful Learning in Laboratory Inventory

In the main phase of the data collection, the MLLI questionnaires were administered in the first weeks of the laboratory, September to October 2017. As required by the authors who designed and validated this instrument (Galloway & Bretz, 2015a), the questionnaires were unaltered. The statements were subsequently categorised during the analysis to give a glimpse into the cognitive and affective domains measured by the instrument. Different from the previous questionnaires, the MLLI was measured with a continuous scale from 0 to 100. Therefore, the data was analysed using parametric statistics. The results are shown in Table 5, which shows that students' expectations of the laboratory can be ranked in order of importance, based on the average scores. In the cognitive domain, they expect to learn problem solving skills (82.12%), to make mistakes and try again (77.57%), and to consider if their data makes sense (71.57%). They least expect the procedures to be simple to do (39.94%), to be confused about how the instruments work (44.75%), and to be confused about the underlying concepts (47.12%). Within the affective domain, students primarily expect to develop confidence in the laboratory (82.45%), to be confident when using the equipment (70.39%), and to be excited to do chemistry (69.96%). They least expect to be nervous when handling chemicals (28.35%), to be frustrated (46.08%), and to feel intimidated (46.67%). In the cognitive-affective domain, they primarily expect to learn chemistry that will be useful in their life (72.39%) and to be intrigued by the instruments (59.59%). They least expect to feel disorganised (28.43%) and to feel unsure about the purpose of the procedures (46.39%).

Triangulated with data from the interviews, this instrument was aimed at resolving sub-question 1b in particular, which will be discussed in section 4.4.

Table 5. Students' learning expectation in physical chemistry laboratory (n=51)

Cognitive Domain	Mean	SD
to think about chemistry I already know.	71.53	16.93
to make decisions about what data to collect.	66.88	17.49
to experience moments of insight.	68.45	18.75
to learn critical thinking skills.	67.53	20.55
to be confused about what my data mean.	57.41	16.85
to consider if my data makes sense.	71.57	15.70
to think about what the molecules are doing.	69.12	20.44
the procedures to be simple to do.	39.94	17.31
to be confused about the underlying concepts.	47.12	20.96
to "get stuck" but keep trying.	62.49	19.85
to be confused about how the instruments work.	44.75	25.08
to interpret my data beyond only doing calculations.	69.61	18.09
to focus on procedures, not concepts.	52.84	17.31
to use my observations to understand the behaviour of atoms and molecules	70.55	18.68
to make mistakes and try again.	77.57	15.35
to learn problem solving skills.	82.12	13.36
Affective Domain		
to worry about finishing on time.	47.10	25.88
to be nervous about making mistakes.	54.94	23.01
to be nervous when handling chemicals.	28.35	22.43
to develop confidence in the laboratory.	82.45	14.39
to be frustrated.	46.08	28.83
to be excited to do chemistry.	69.96	16.83
to feel intimidated.	46.67	17.93
to be confident when using equipment.	70.39	17.96
Cognitive-Affective Domain		
to feel unsure about the purpose of the procedures.	46.39	24.00
to learn chemistry that will be useful in my life.	72.39	24.70
to worry about getting good data.	57.24	18.77
to feel disorganised.	28.43	23.51
to worry about the quality of my data.	50.31	24.73
to be intrigued by the instruments.	59.59	21.92

4.3. Student Interviews on Learning in the Laboratory

Two students in the pilot phase and six third-year students in the main phase agreed to participate in the semi-structured interviews, whereby four of them were males and four were females. One was a student whose English was not a first language. In the rest of this article, excerpts of each of these interviewees will be labelled with superscripts a and b (pilot phase) and 1 to 6 (main phase). The interview protocol consisted of three big sections on pre-laboratory, Nature of Science, and information management. Each question aimed to elicit their experience in the laboratory from cognitive, psychomotor, and affective viewpoints. These interviews were designed to gauge deeper into their responses to the Meaningful Learning Laboratory Inventory (MLLI) questionnaires administered earlier.

Each interview took approximately 40 to 60 minutes. Each participant gave their consent to be recorded. Their responses were transcribed verbatim and fed into NVivo for qualitative data analysis, according to phenomenological methodology. Coding was used to identify salient features and emerging themes.

From the initial two categories, further themes emerged from the data. Firstly, the pre-laboratory section elaborates into students' personal goals, their preparation for the lab, their views on pre-laboratory works and their effectiveness to promote learning, narrowing down to their experience of pre-laboratory videos and further recommendations. Secondly, the information management section elaborates into how they manage information during the laboratory, the chemistry behind the experiment and the relevance of pre-laboratory therein, and their assessment of their own accomplishment after the laboratory. A third category, affective domain, emerges as participants express their feelings during laboratory work and assess their own confidence. Additionally, challenges in the laboratory, demonstrators' role, and post-laboratory aspects are also discerned from the data. These themes are visualised in Figure 16.

4.3.1. Prelaboratory Work

The qualitative data was analysed using NVivo (Version 12 for Mac and Windows, 2018), according to the phenomenological methodology. Several key themes pertaining to the inquiry emerged from the data.

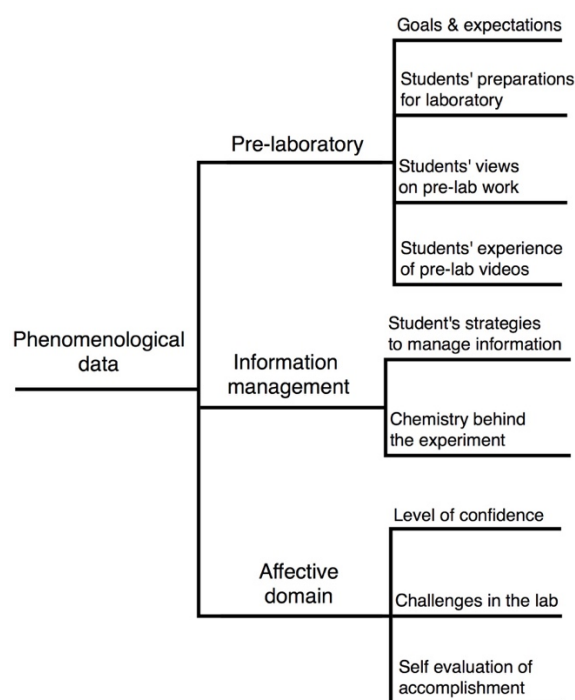


Figure 16. Clusters of themes from the prelab interview data

4.3.1.1. Goals and expectations. Before commencing a laboratory work, students have their own goals and expectations. This may reflect the goals set by the laboratory course designer, as written in the laboratory manual. A student set the goal to 'determine the relaxation time of caffeine' and 'learn how to use the bench-top NMR spectrometer'², whereas another aimed to 'determine the second order rate coefficient' by using 'UV 1800 spectrometer to measure absorbance'³.

Other students were more pragmatic and focussed on their personal goals, as they mainly just hoped to 'finish part 2' of an experiment^{4,5,6} and 'get as much done as possible'^{1,a}. Having finished part 2 of a computational experiment, which incorporated investigation aspects, a student hoped 'to make sense' of the data that she had obtained in the first, prescribed part⁴.

As for the importance of being well-prepared for the laboratory, students think that they would be less confident going into the lab without the pre-laboratory^{b,5}. It helps them 'make sense' of the experiment they conduct^{a,4}.

4.3.1.2. Students' preparation for laboratory. For each experiment, a suite of pre-laboratory resources is available. They may vary but it typically consists of laboratory manuals (both online and printed), pre-laboratory videos (background theory,

experimental skills, and post-laboratory data analysis), online discussion boards, and supplementary materials such as academic journal articles.

The interviews shed some light on how students prepare for laboratory work. Students read through the manuals^{1,4,5,6,a,b} and a link to academic journal articles^{4,6}. The lab manuals contain relevant information about the experiment and, to some extent, some background theory⁴. Essentially, the printed manual is students' point of reference as they proceed through the experiment. In the case where an article was linked to the manual, a student had difficulty understanding it⁴. She was trying her utmost to do the experiment according to the procedures therein but she was struggling. It may relate to the academic level of English in the article, or her being non-native English speaker, or both. The article proved to be very important in the success of the experiment, as one student who did not read it found it very challenging to do the experiment. She concedes, 'I thought the preparation last week would be sufficient but it wasn't ... I should have read the scientific paper that they provided for us.'⁵.

Although the quiz was not specifically designed as a part of pre-laboratory in the physical chemistry laboratory, students appreciated and used it whenever available^{1,4}. In one of the experiments, students were given 10 questions to probe into their understanding of the topic prior to the laboratory. There was no mark given but a student contended, 'answering these [questions] will improve our understanding of the experiment'¹.

Students watched pre-laboratory videos to prepare for the experiments^{1,2,5,6,a,b}. Not every experiment had complete parts of videos (background theory, experimental skills, and post-laboratory data analysis), but when they were available, students made use of these resources. They were particularly useful when students had not learnt the topic in the lectures, as one student conceded that he 'tried to figure out the settings ... cause [the lectures] haven't really covered relaxation times'⁶.

They also used the online discussion boards to prepare for the laboratory^{1,2,3,5}. These are an online forum whereby students can post questions or raise an issue regarding an experiment or data analysis. In the following subsection, they applaud the effectiveness of discussion boards in helping them prepare and analyse data.

4.3.1.3. Students' views of pre-laboratory work. Students appreciated the pre-laboratory resources available to them. Regarding the pre-laboratory videos, one student described,

'I think the videos are definitely helpful because, for example when you have to use a new instrument it's hard to imagine what's going on when there's a lot of steps you have to follow that's written in the manual, but when there's a video showing you, ... it's much easier and it gets less time to get used to the machine when you're in the lab.'²

Depending on the experiment, the pre-laboratory videos usually consist of one or more of the following separate parts: (1) brief theoretical background, (2) experimental skills and instrumental operation, as well as (3) data processing and analysis. They are always accessible on the website hosted by the university any time students need them.

The videos were particularly helpful when students did an experiment on a topic that had not been taught in lectures^{b,2}, as a student conceded, 'the PCA (principal component analysis) experiment was quite difficult. It took some time to figure out what was going on. [We would like] some sort of explanation on what PCA was, ... We had a few suggested articles, but [they] were like actual journal articles that aimed at people who understand what PCA is.'²

Students believed that the online discussion boards were effective in helping them prepare for the laboratory^{2,5,b} and write up the laboratory report^{1,3}. A student reflected, '[the online discussion boards] started last year ... and it was full. Everyone was asking lots of questions, you could find out information'². One of the beneficial factors of online discussion boards that appeals to the students is its flexibility⁵ and accessibility³. Students can ask a question or raise an issue specific to an experiment and the laboratory instructor, who is also a lecturer in physical chemistry, would respond⁵. Other students can also respond. The discussion boards also allow for shared problems to be solved together^b. '[It is] easy when people have the same issues [and] more useful when we have the same struggles.'¹ For those who are not very keen on asking a question themselves, they can see if 'other people may have the same question. They asked it for you and you don't have to.'² Typically, the rate of response is high^{1,5}, and it is helpful when all students have to write their laboratory reports between the laboratory sessions. A student lauded,

'I think the discussion board is best by far, because it provides a sort of channel between yourself and Dr X (the laboratory organiser and lecturer).'³

Despite all these, one student apparently wished that there was some sort of face-to-face discussion prior to the laboratory session, as she suggested, '[m]aybe it's personal but I feel sometimes I understand what's going on but if someone asks me, I realise maybe I don't understand it that well. I think 10 minutes face-to-face will be more helpful'⁴. As described in the pre-laboratory review we have published elsewhere (Agustian & Seery, 2017), discussions are known and used as a form of pre-laboratory work.

A student even compared the pre-laboratory in the physical chemistry laboratory to other laboratories. He believes that '[t]hey're a lot more helpful and organic and inorganic labs, ... [as] it goes over what you're gonna be doing. ... You know in advance. [The pre-lab videos] show you how to do it'³. He further describes,

'[I]n the second year, inorganic was the worse. There w[ere] no videos at all. Sometimes there w[ere] 10 questions, you just look up the answer on the internet. And then once discussed you type in another tab and you know, it doesn't seem very applicable ... [T]he organic has some videos, experimental techniques from Dr Y, but they were few and far between. How to use the machines, rather than how to do the experiment. So instead of like saying on this experiment you're mixing this, this is how to operate as you use, it would just be this is how to submit an NMR sample, this is how to use the IR.'³

A student summarised her physical chemistry laboratory experience as '[h]ere you know what you are expected to do.'⁴ She was a student on a sandwich programme who was doing a year abroad at this university.

4.3.1.4. Students' experience of pre-laboratory videos. The overall experience of pre-laboratory videos is positive. They 'make [students] feel more confident, knowing, and understanding what techniques are expected of [them]'⁵. They also serve their purpose of recalling prior knowledge, by 'refresh[ing students'] memory'³, particularly prior to the very first laboratory session after a few-month vacation break.

Although not every experiment has a pre-laboratory video on background theory, whenever it is available, students appreciate it^{b,2}, as one described, '[i]n some of the videos they explain the theory behind it, which is easier [and more engaging] than reading through the manual'². The background theory content in the video helps

'reinforce ... data handling skills'^a, as it provides the students with some relevant information to process prior to the laboratory. Another student articulated,

'I guess it depends what the aim is. [As for] the best base for going into the lab, the video does the best job by itself. It's the most accessible, the easiest thing to do, just watching the video, compared to reading articles. That takes more effort ... but you still need some background reading. Especially if it's a concept you haven't done very much in class.'⁶

Students also appreciated the fact that the videos were designed specifically for the experiment^{1,3} and not some generic instructional clips on how to operate an instrument, such as in another laboratory³. They were 'very useful'³ in providing students with some essential information about background theory, the experimental skills expected of them, and some guide to data processing. They also provided a context 'because you can get all these theoretical explanations [and their] appl[ication] ... to the real world'^a.

Compared to other types of pre-laboratory activities, videos were preferred 'because [they are] something different. [Students] fe[lt] like [they were] using [their] brain differently'⁵. They 'are visual, so it helps'⁴ those who learn better through visualisation of concepts and instruments. A student maintained,

'It puts all the right things in context. You see the actual lab. You see the equipment, which button to press, by which you can visualise what you'll actually be doing in the lab.'⁶

In terms of the time needed to watch the entire video, a student contended that because '[t]hey're usually under 10 minutes, ... it doesn't take up much of [his] time.'² This suited students' available time to prepare for the laboratory, as one pointed out, 'I ... need like half an hour to prepare for a lab'⁵ in between other learning tasks she had to do. A few minutes spent on preparing for laboratory makes a big difference in students' laboratory work completion rate, as one maintained, '[u]sually an experiment with the video goes much faster'².

In terms of content, the pre-laboratory videos are considered not only concise but also well-structured, 'start[ing] from beginner's knowledge'³. In a video on background theory, it 'always builds up from the start, like basic theory'³. It is noteworthy, however, that students agree 'that the point of the lab isn't to teach you theory. It's to improve your skills at writing lab report essentially [and] using the equipment'^{5,6}. Whenever theory is discussed, it is expected to be 'briefly outlined ...

[and] not too in-depth'⁵. One student reflected, the videos 'were ... clear, ... formatted nicely ... [and devoid of] information overload ... [I]t ... goes along in chunks, ... nicely laid out'^a.

Pre-laboratory in the physical chemistry laboratory is designed to support students' learning. The extent to which it serves its purpose varies from student to student. Ideally, it should help students to prepare for the laboratory with the purpose of reducing cognitive load during the experiment, so they can focus more on learning new skills and thinking about the actual chemistry behind the experiment. Within the continuum of learning associated with laboratory, it mainly addresses learning *in* laboratory. However, the interviews provide some insights into how students also benefit from it after the laboratory session, as they begin to write up their report, a stage known as post-laboratory. One student intimated, 'When writing up my report, I used the videos.'³ They provide a context in which students 'understand [the experiment]'⁵ better.

On that note, a student believed that of all pre-laboratory videos available, the 'most useful video [is] the post-lab analysis. ... It's a brief video on how to present your data, what would the best method be. It guides you in the right direction, so you don't waste your time working out what you need to do.'³ This part of pre-laboratory videos 'was very helpful, because there was a guide to the data [by] putting it to context with the video, ... [It] made a big difference to [their] result ... [and h]elped [them] to understand it'⁵. For these reasons, the pre-laboratory videos are relevant not only to the experiment they conduct in the laboratory, but also the write-up process^{3,4}.

The interviews also provide some user-initiated suggestions for improvement of the pre-laboratory videos. In terms of content, students felt they could benefit from more 'background theory'⁶ and a 'recommendation on further reading'¹. There could be 'more details ... [and] more examples ... [of w]here the theory could be applied'². In a case where an experimental technique is new, or the theory is not yet covered in the lectures, a pre-laboratory video on experimental skills is highly needed^{2,3,6}. Videos on data analysis are also much appreciated⁴, preferably for each experiment that requires elaborate analysis.

Students suggested that the videos came with subtitles, to cater for non-native speakers in particular. One student conceded, 'This might be trivial, for me a lot are fine but for international students, understanding Dr X could be quite difficult. ... Subtitles would be helpful. Or in the comments. A manuscript [sic].'³ An international student participant indeed found it challenging to follow the narration on the videos⁴. In terms of layout and presentation, the video could be designed in a 'more visually interesting'^a fashion.

4.3.2. Information management in laboratory

Students were asked to describe how they managed the amount of information during the laboratory. Discussion was directed towards how pre-laboratory affected, if at all, their strategies in managing cognitive loads in laboratory. In terms of the amount of information they had to deal with, responses were twofold, depending on which experiment, either 'overwhelming'^b or insufficient⁴. One student lamented the unfamiliar terms and new information in principal component analysis (PCA) experiment,

'[T]here was a *lot* of new information [in PCA experiment]. You had one lab session to do your experiment and then you have to look at your data and understand what it means. ... [T]he demonstrator ... explains to you what the parameters on the gap are. And he uses like a lot of statistical jargons, and we were like... what does this mean? Explain it to me in human terms'²

whereas another student thought there was *not* enough information available to her during the computational experiment:

- 4: I didn't think they gave us too much information. ... It was not overwhelming. Even if they could push us a little bit more, it wouldn't be overwhelming.
H: You said you could manage the information, why were you stressed then?
4: Because there was not enough information. ... They explained what I had to do, but not *why* I had to do it.

4.3.2.1. Students' strategies to manage information. Students had different strategies in managing information in the laboratory. Whatever the strategies were, they agreed that pre-laboratory helped them in doing so^{2,3}, as one student described, '[W]e had the NMR lecture course which definitely helps so we know what relaxation times are, roughly. But prelab material was very helpful. We had 10 or 11 pointers to consider before coming to the lab, so once you read through that, you know what you're doing. It's much easier to handle all the information'².

Prior to coming to the laboratory, they could find some relevant information they probably needed during the experiment from the discussion forum³, on which they could ask questions, informed each other, or became a silent reader and gathered any relevant information from the discussions⁵. Peer support is also one of the factors that is helpful in coping with the amount of information and the learning opportunities available in the laboratory, as one student put it, 'I would often ask my lab partner for guidance and I would try and look at it from my point of view, and I try to see if my lab partner is thinking the same thing. Because sometimes I would doubt that I got it right'⁵.

As the experiment proceeds, these strategies also carry through. Keeping an organised laboratory book is one those ways of managing information and the ever-important data. One described, 'We get mark for lab notebook, tidiness etc. You get 15 marks overall for keeping your lab notebook, so... like here [showing notebook], and then writing what you're doing as you go along, drawing diagrams. And that encourages you to write things as you go along. Whereas if there's no mark available, I'd be like... fine, yeah... I won't write that, and I'll remember that when I come to it, but it helps because the mark is available'³. A small incentive is therefore still favourable.

Time and again the interviews give an account of how prior knowledge obtained from either lectures or pre-laboratory is essential in facilitating deeper learning, as this excerpt described,

3: [S]ometimes in inorganic [chemistry], it's chemistry we haven't seen before. So, why would we do that? Give us something we can relate to, something we know about. Otherwise what we're doing is basically a shaft. You're just copying the instruction and doing everything without actually knowing what's going on. So it's good to have done the theory in the lecture before [the] lab.

H: Have you learnt any of that from the prelab?

3: Yeah, definitely. Or even if I haven't learnt it, it refreshed. [For example] kinetics, 2nd year, I think first semester course, ... I haven't seen it in about a year. The prelab went over that and refreshed my memory³.

4.3.2.2. Chemistry behind the experiment. Students acknowledge the importance of thinking about the chemistry behind the experiments they conduct in the laboratory^{1,2,4,5,6}. This can be facilitated, partly, by allowing them to investigate a topic, after they are familiarised with the theory and experimental aspects, such as what is organised at the physical chemistry laboratory in Year 3. A student argued

that in the first year, where laboratory is entirely prescriptive, 'It'll be very easy to do [the experiments] absent-mindedly'¹. Although it was challenging, the investigation part of laboratory this year has been seen as an opportunity for learning^{1,2}.

Familiarity with the subject topic of the experiment during the lectures also helped students focus on the chemistry, or apply the knowledge into practice, as one described, 'It's often quite applicable to what we've done in the course. In organic, you literally just do what you've done in the lecture slides. So you can actually look back in those whilst writing your report. In physical, sometimes it's a little bit more difficult but often we use equations we've seen before'³. The prior knowledge they have got in either lectures or pre-laboratory is essential for the success of learning *in* the laboratory. An indication of this success is when students know why they do what they do. One conceded, 'Sometimes you know the steps you have to do but you don't know why you're doing that exactly'⁴.

Time was again seen as a limiting factor, as one student complained, 'I didn't really get the chance to, because there was quite a lot to do in a short amount of time, so I have to focus on completing it. At times I didn't get to think about the chemistry [behind the experiment]'⁵. 'You just have to be wary of time and really think about what you really need to know, what was interesting information'^b.

4.3.3. Affective Domain

Students' experiences in the laboratory ranged from 'fun'² to 'frustrating'^{5,6}. One student described, 'doing the experiments like seeing the application of science that we're learning is creatively fulfilling'^b. Another student conceded that the experiment itself was not stressful but 'processing the data [was] a lot harder'¹.

On the other hand, other students felt that they somewhat stressed⁴, out of depth^b, confused⁵, doubtful⁵, and quite frustrated⁶. 'Sometimes everything is so new and you feel alone'⁴. One reflected,

'The experiment today... this one was quite frustrating, I would say. I know that sometimes frustration can be a good thing, as it can motivate me to know more. But today at times I felt like I was being hindered by the wording and thing in the lab manual. The way it was explained to me, which doesn't feel like something that should hold me back.'⁵

4.3.3.1. Level of confidence. When asked to rate their level of confidence on a scale of 0 to 10, students' responses ranged from 2 to 9^{1,2,3,4,5}. One student claimed,

'I'd say... about 6. ... Often before I do something I check with my partner and check with the demonstrator, because doing something and getting it wrong is a lot worse than asking someone. ... And if you make a mistake, some of the experiments takes 2 hours to run etc. If you do something wrong in the first stage, that's kind of ruin the whole lab. So I often do double check everything. ... So those are the learning point, experimental, confidence, and now back myself using the machine'³

Another student conceded that confidence in the laboratory can also change over time, as he revealed, 'Depends on the experiment. The NMR was like a solid 8.5 ... The PCA... started off at 2. The first part where you measure the UV/vis spectra, that was like a 9, but when it came to PCA analysis. You're kind of descending over time'².

Credit goes to the pre-laboratory videos in making a student feel more confident⁵, as one student intimated 'I really like the videos. I think they make me feel more confident, knowing and understanding what techniques are expected of me. ... Today I would say... maybe 5. I felt completely out of my depth, not at ease. ... The first one maybe a 7? Partly because we've done physical lab before with that, which was really helpful'⁵.

4.3.3.2. Challenges in the laboratory. This theme emerged as students reflected on their laboratory experience. Technical failure is one of the challenges they had to face⁶, as one recalled, 'First half of that session was fine but in the afternoon the machine kept freezing so we couldn't really finish everything in the experiment. But Dr X had a look at it and found out that something in the machine wasn't stabilised. ... We spent 2.5 hours trying to run the same scan over and over again'⁶.

Time constraint was seen as a limiting factor in thinking beyond the procedures, as one described, 'I had to jump from task to task ... without trying to think about ... the [scientific] context. ... You didn't really have the time to sit and think about it.'^a It can be disheartening when you do all the results and all the discussion but then your results just haven't worked'³.

In the previous setting of the laboratory, the investigation was considered 'daunting'^b as students had to figure out their own experiment based on some information provided. In the ensuing setting, the arrangement of four weeks prescribed laboratory and two weeks investigation was changed into six weeks consisting of three one-week prescribed laboratories immediately followed by their

corresponding investigation week. The interviews revealed that this setting was considered more manageable^{4,5}.

4.3.3.3. Students' self-evaluation of accomplishment in the lab. Students were asked to evaluate their own accomplishment in the laboratory, in their own words. In general, they referred to the goals they mentioned at the beginning of the interviews^{2,3,5,6}. One student said, 'I definitely learnt a lot of new techniques. Physical chemistry teaches you a lot of instruments, how they work'². For instance, students learnt how to use UV spectrometer in measuring absorbance. One described, 'By the end, we had 25 sample so I know exactly how to hold the cuvette, how to put it, how to hold the baseline etc'³.

Although laboratory report can be 'hefty'¹, report writing skills are also considered as a learning accomplishment². Students learnt 'how ... to look stuff up to understand [what they write and] how to handle and process [their] data'². In the context of learning continuum in the laboratory, a student held the view that they 'can understand everything only after [they]'ve done everything, not only the prelab'⁴. Also, because they worked in pairs, they learnt how 'to work effectively as a team'².

In terms of deep learning, a student intimated that the laboratory helped her to 'think in new ways'⁵, by applying the knowledge in a new context. She continued, 'It's a big part of being a scientist, to be able to apply the knowledge. I think what I get from it is valuable'⁵. Pre-laboratory plays an important role in paving the way to these higher order thinking skills.

4.4. Dimension 1: Meaningful Learning in the Chemistry Laboratory

The findings from both quantitative and qualitative data reveal some salient features of laboratory work in the context of the physical chemistry laboratory. The project was set up with the purpose of investigating characteristics of meaningful learning experience in the laboratory, particularly with regards to pre-laboratory work. Deploying two sets of questionnaires and a few rounds of interview data collection, the research questions pertaining to this part of the study will be addressed in the following sections and emerging themes will be discussed as follows, according to the research sub-questions 1a, 1b, 1c, and 1d, respectively.

4.4.1. Preparation for Laboratory Work

The body of knowledge in the field of pre-laboratory is growing, as elaborated in section 2.4. Findings from previous studies in this area report at least seven forms of pre-laboratory activities used by laboratory course designers to help students prepare for laboratory work apart from reading the laboratory manual, *viz.* pre-laboratory lectures, in-laboratory discussions prior to the experiment, pre-laboratory quizzes (both pen-and-paper and online-based), pre-laboratory videos, interactive simulations, experimental plans, and mental preparation. Each of these forms of pre-laboratory activities has its own characteristics, either in terms of purpose, pedagogical emphasis, and presentations, or in terms of strengths and weaknesses. They have been used either on its own or in combination.

In this study, students use different methods to prepare for laboratory work. The available resources, *i.e.* laboratory manual, pre-laboratory videos, online discussion forum, and supplementary articles, are mostly used according to students' needs. Most of the participating students use a combination of some or all of these resources. Students applaud the effectiveness of these resources not only in preparing them for the upcoming laboratory work, but also in preparing and analysing their data. However, this raises a question as to whether they are more effective as a whole, as a part, or as a combination of some of the parts. It also begs the question if laboratory course organisers should think of these activities in terms of efficiency. For example, given the positive evaluation and efficacy of pre-laboratory quizzes in reinforcing correct understanding of the experiment (Chittleborough *et al.*, 2007) by 'forcing' students to prepare in advance of the laboratory (Gammon & Hutchinson, 2001), it may be worth considering adding an element of quiz in the existing pre-laboratory activities. It may also be relevant to ponder if the laboratory organiser should revisit the voluntary nature of current pre-laboratory work.

The evidence from the interviews, such as previously presented in 4.3.1, shows that some students do not prepare for the laboratory at all. In a reflective and retrospective account, they admit that their being unprepared has impeded some aspects of learning in the laboratory. A slight modification of the existing pre-laboratory may just be what is needed. Accordingly, if shifting from voluntary to

compulsory pre-laboratory work is deemed too demanding a task for students, perhaps incentivising them with a small fraction of laboratory mark for completing pre-laboratory work (which could be indicated with a successful quiz submission) could be an alternative solution. Insights from the interviews show that students still appreciate the value of answering experiment-related questions prior to the laboratory. Previous studies such as that of McKelvy (2000) and Jolley *et al.* (2016) are an example of how graded, compulsory pre-laboratory quizzes are embedded into pre-laboratory videos. Their findings demonstrate that students benefit from this combination, reflected in high levels of perceived preparedness and their overall positive attitude towards pre-laboratory, despite the compulsory nature of pre-laboratory quizzes.

The pre-laboratory videos in particular have been widely used for several purposes. Evidence from the first set of questionnaires on learning in the laboratory and the interviews indicate that students use the videos specifically to:

- reinforce known technical and instrumental skills, and introducing new ones, in a visual and contextual manner;
- recall prior and introduce new chemical concepts, especially difficult concepts not yet covered in lectures (partly due to the rotation system);
- help them with data presentation and data analysis skills, such as representative calculations;
- help them to feel more confident about successfully conducting the experiment;
- motivate them to complete the experiment more efficiently; and
- support the post-laboratory work, particularly the write-up of laboratory reports.

Some of the perceived purposes of pre-laboratory videos mentioned above are in line with the previous studies, such as Box *et al.*, (2017) and Schmidt-McCormack *et al.* (2017). More of this has been elaborated in section 2.4.1. but there are also other salient features worth considering when designing this form of pre-laboratory work. These purposes are also mirrored in the evidence for learning by means of other form of pre-laboratory activities made available in the setting of this study, namely online discussion board. Here lies, I argue, the relevance and importance of

discerning research issues such as ‘purpose of pedagogical instruments’ from the ones who actually use them, in this case the students, and not only relying on what the curriculum designers envision such purpose would have to be. Only then can the synergy between the intended, implemented, and attained curriculum levels (Thijs & van den Akker, 2009) be accomplished. In details, they describe these levels in terms of six forms of curriculum, as shown in Table 6. This typology of curriculum representations in terms of levels and forms also justifies the key issue investigated in this research, *i.e.* students’ learning experience, and reasserts the importance of providing evidence for learning reflected in the attained level. All too often, university course designers and assessors rely too heavily on learning outcomes measured with standardised tests (learnt curriculum form), but oversee the importance of substantiating students’ perceived learning experience (experiential curriculum form).

Table 6. Levels and forms of curriculum (Thijs & van den Akker, 2009)

Level	Form	Specification
Intended	Ideal	Vision (rationale or philosophy underlying a curriculum)
	Formal/Written	Intentions as specified in curriculum documents
Implemented	Perceived	Curriculum as interpreted by its users (usually teachers)
	Operational	Actual process of teaching and learning
Attained	Experiential	Learning experiences as perceived by learners
	Learnt	Resulting learning outcomes of learners

Thijs and van den Akker further argue that the distinction emphasises the different layers of the curriculum and demonstrates the substantial discrepancies between the various forms. They assert:

... an often-voiced desire is to reduce the gap between dreams, actions and results. The bottom layers often provide more possibilities for observation and assessment. Especially implicit assumptions and views are not easily defined in a clear-cut and unambiguous manner, while they do affect the educational practice (Thijs & van den Akker, 2009, p. 11).

4.4.2. Students’ Goals and Expectations

The entire discussion on students’ goals and expectations of laboratory work supposedly mirrors the one on the role of laboratory in undergraduate chemistry

education, as previously argued in section 2.1.1, which includes, but not limited to, specific practical skills, scientific reasoning, creativity and problem solving, social relationships, affective domain, and understanding of the nature of science. The alignment between these two domains echoes that of the curriculum levels and forms discussed in the previous section.

Previous works exemplify the delineation of goals for laboratory, such as Bruck *et al.* (2010) from a faculty perspective and DeKorver & Towns (2015) from a student perspective. The former elucidates common goals such as laboratory skills and techniques, as well as critical thinking skills and experimental design, apart from assorted other goals predominantly associated with different branches and levels of chemistry in higher education (Figure 17). On the other hand, the latter reveals that students' goals have largely nothing to do with the faculty perspective. For them, the ultimate goal for laboratory work is to finish the experiment in time, preferably early. DeKorver & Towns (2015) argue that this could be associated with the affective domain, as students describe 'feelings of enjoyment due to finishing early and feeling bad about being the last to complete the experiment' (p. 2033). I believe this is arguable, but the fact that they put so much emphasis on finishing the experiment early, as opposed to, *e.g.* higher order thinking or technical skills, strikes a discordant note between the faculty and student perspectives. The authors also admit that this is the case indeed.

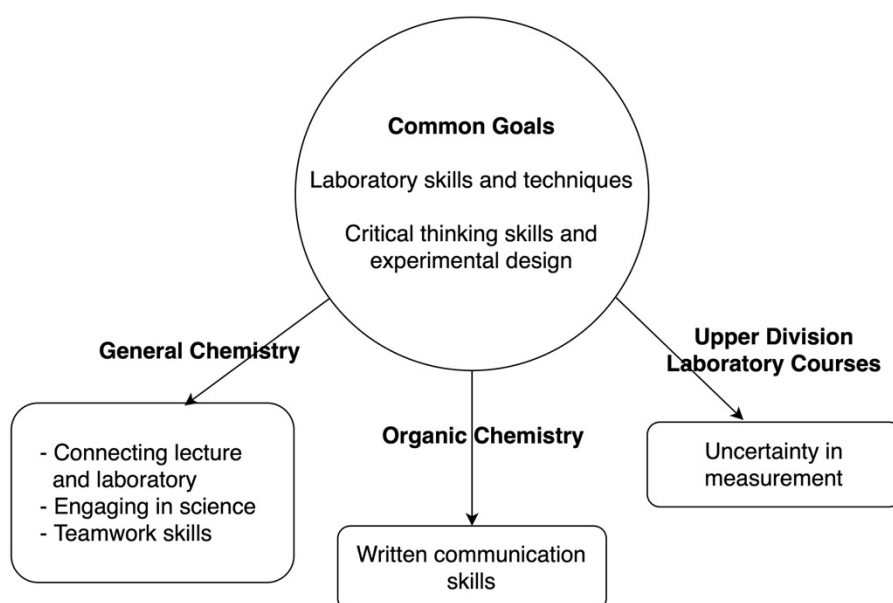


Figure 17. Faculty perspective on laboratory goals (Bruck *et al.*, 2010)

The present study offers a rather different sketch. Indeed, students set their goals based on which experiment they are going to perform. These goals are usually articulated in a direct reference to the ones stated in the laboratory manual, such as to determine the relaxation time of caffeine. A majority of students, however, expect to learn about problem-solving skills and making sense of data, as can be discerned from the MLLI questionnaires and the interviews. Critical thinking skills are also considered important, which is actually aligned with the common goals of laboratory work synthesised by Bruck *et al.* (2010) above. Similarly, the interviews shed some light on how students engage in asking questions and making decisions related to the laboratory work, which are among the manifestations of higher order cognitive skills in the laboratory (Zoller & Pushkin, 2007).

The reference to higher order thinking skills in Bloom's taxonomy and the role of the laboratory therein can be found in the early work of Hofstein and Lunetta (1982). They argue that the laboratory plays an important role in developing these higher cognitive skills in a way that conventional lecture-based education and its corresponding assessment do so but to a lesser extent. Accordingly, Stephenson and Sadler-McKnight (2016) found that higher order cognitive skills such as critical thinking skills can be developed in the laboratory through dialogic interactions between students and their peers and between them and experts (such as demonstrators and supervisors), whilst exchanging information and interrogating ideas. It may be relevant for laboratory curriculum designer to evaluate the extent to which students acquire higher order cognitive skills.

In the framework of complex learning, elaborate mental preparation is needed to perform learning tasks with higher order cognitive requirements (van Merriënboer *et al.*, 2003). As argued before, laboratory exercises entail that these learning tasks ought to be performed well. We also argue elsewhere (Agustian & Seery, 2017), that mental preparation is used and, indeed, required in order to prepare for laboratory. Evidence from goal setting and expectations of laboratory work substantiated in this study indicates that students actively use mental preparation (see subsection 2.4.2.7) to oversee the required amount of thinking they will have to deliver in the laboratory, which brings us to the next discussion on how students manage information in the laboratory.

4.4.3. Managing Information in the Laboratory

Much of what we know about the nature of information in the laboratory, the amount allocated to the experiment at any given time, the distinction between relevant and background information, the tension and frustration it could create, the capacity of both working and long term memories a student can handle at one time, and the evidence-based pedagogical approaches that could alleviate this tension, can be properly explained by cognitive load theory (Sweller *et al.*, 2011), as presented in section 2.3.1. Chief and specific to the context of the laboratory is the work of Johnstone and colleagues from the 1990s up to the 2000s, encapsulated in their information processing model. Essentially, this model distinguishes the way seasoned scientists and novice scientists — in this case, chemistry students — perceive and respond to the information presented to them during any given laboratory exercise. Experienced scientists have sufficiently well-interconnected schemata that afford them to focus on relevant information, instead of bothering with irrelevant background noise. In contrast, novice scientists think all information is important, or cannot distinguish between the signal and the noise (Pickering, 1993), or cannot decide to focus on what and when. Consequently, they are overwhelmed by the amount of information they have to handle, which often leads to a cognitive ‘shut down’, whereby they decide to blindly follow the experimental procedures prescribed in the laboratory manual and abandon the will or interest in thinking about the chemistry behind the experiment they conduct, all as long as they can finish the work.

To some extent, this feeling of being overwhelmed by a plethora of information is voiced by a few students in the present study, as the interview and questionnaire data indicate. However, zooming out, most students actually ‘feel that [they] can manage the amount of information that [they] have to deal with during the experiment’ (statement 17 from the Student Questionnaire on Learning in the Laboratory), reflected with a high median. Similar findings are also discerned from other statements in said instrument (statements 18 and 19). In fact, to some students, the available information is considered insufficient. This raises a question as to which information should be presented to students so they are well-equipped

to conduct the laboratory exercise and the degree to which this information should be given, particularly when it comes to challenging topics such as principal component analysis and computational modelling.

That being said, the existing pre-laboratory activities are reported to have a positive impact on the way students manage information and cognitive load in the laboratory. This is partly reflected in the statement 12 of the aforementioned questionnaire, which reads 'The information I learn from the pre-lab videos help[s] reduce the stress of dealing with too much information during the experiment' (median 5). If the students participating in this study represent the population of undergraduate chemistry students in this particular teaching laboratory (upper-division physical chemistry), then this finding is a good tiding. The main purpose of pre-laboratory work as argued in this research is ultimately reducing cognitive load *in* the laboratory, by delegating some of the relevant information to the preparation stage. It goes without saying, further substantiation may be needed, especially the degree to which the cognitive load is reduced and the manners in which various forms of pre-laboratory activities affect this load reduction.

In the present study, students use several strategies to manage information in the laboratory, *viz.* by chunking information in the form of pointers to consider, attending to similar questions that have been answered on the online discussion forums, or by keeping an organised laboratory book. Peer support both during pre- and in-lab sessions also helps them manage the information. As mentioned above, the data confirms the essential role of prior knowledge in reducing cognitive load, as previously reported (Cook, 2006; Seery, 2009, 2012, 2015). The current setting of laboratory in which students perform three cycles of one prescribed experiment followed by an investigation session is considered more manageable in terms of information management, as opposed to the previous setting in which four consecutive prescribed experiments were followed by two weeks of investigation.

4.4.4. Pre-laboratory Work and Affective Domain

The importance of the affective domain in the laboratory has been lauded by a host of scholars in chemistry education research, such as Pickering (1993), Hofstein & Lunetta (1982, 2004), and Galloway *et al.* (2016). However, knowledge in this

specific aspect of laboratory education is still scarce. Previous research findings demonstrate that students have diverse affective experiences that largely do not meet their expectations (Galloway & Bretz, 2015a, 2015b). A lack of interest or motivation could be detrimental to learning. It takes away the drive behind the core concept of meaningful learning, in which the triad of cognitive, psychomotor (conative), and affective domains are interconnected and supportive of each other.

In this study, developing confidence in the laboratory is the most important goal as far as affective domain is concerned, according to the MLLI survey. Pre-laboratory, particularly the videos, helps students build confidence during experiments. In the previous studies conducted by (Towns *et al.*, 2015) and (Seery *et al.*, 2017), confidence in the laboratory is also reported to be an affective dimension that is closely related to pre-laboratory videos. The range of affective experience in the laboratory goes from fun to frustrating. Students find modes to turn the negative experience of laboratory in all its nuances into something that can motivate them. Decades ago, Amsel and Ward (1954) found that frustration has certain motivational properties by providing drive stimulation which gives directive properties.

Chapter Five. Students' Views of Science

This chapter will present findings and discussions on the second part of the study, concerning students' views of the nature of science.

5.1. VNoS and Student Interviews on Nature of Science

This section is divided into two parts of the research stage focussing on the nature of science in the laboratory. The first one results from the qualitative part of data collection done in the first half of this PhD. The aim of this phase is to explore students' views of NoS and get a general impression of their level of understanding. A possible association with prelab is also explored. The data from this exploratory phase informs the design of the next phase, which is more evaluative.

5.1.1. Phase 1: Exploration

One of the research questions being investigated in this PhD is to what extent the pre-laboratory informs students about Nature of Science. Students were asked their views on a statement about one of NoS aspects, knowledge, as follows:

Some scientists believe that explanations of chemical phenomena, such as atomic theory, are accurate and true descriptions of atomic structure. Other scientists say that we cannot know whether or not these theories are accurate and true, but that scientists can only use such theories as working models to explain what is observed.

The interviews also probed into their experience with regards to science in general and the extent to which instructional features in pre-laboratory informs them about NoS.

5.1.1.1. Students' perceptions on nature of science. Students agreed that theories are working models to explain what is observed^{2,3,5,6}. They all believed that pursuit for knowledge in science is an ongoing process. One student maintained, 'I'm leaning more towards the second one. I find it difficult to be able to ... believe that you can know something definitively'⁶, whereas another one argues,

'I think it's true how a lot of it is just a model that helps explain what's going on, because for example, molecular orbital theory, is a big theory that explains a lot of stuff but it's more a mathematical approach to explaining something, as far as I understand.'²

Students acknowledged that knowledge is not static^{1,2,5}, and ‘that is the interesting thing about science, how it’s always changing’². A student held the view that ‘[w]e can only use the knowledge we’ve got, then ... we build up our repertoire using that knowledge’³. ‘People thought the atom [was represented by] the plum pudding model, a mass of positive charge and negatively charged electrons. ... [We know now that] it expands and it completely changed, just like the whole atomic structure. It’s been developed over the past centuries’². As such, knowledge is tentative and ‘will keep developing’¹.

The discussion on this topic also gave a hint of how students did not subscribe to scientism^{1,2,4,6}, as one asserted, ‘[t]here’s so much we don’t understand in the world ... to say something is absolutely the way it is’⁶. Science aims to explain how nature works, as one put it rather boldly, ‘the point of science is to find the truth [about nature]’², but another concedes, ‘I don’t think we know the whole truth’⁴.

Scientific methods are among the aspects of Nature of Science and students acknowledged the importance of applying these^{2,4,5}. One intimated, ‘those scientist that don’t believe it’s true, I can understand their viewpoint, because they want to see evidence ... and science is collecting evidence’⁵. In a sense, ‘science is a bit philosophical’², in which one cannot just have faith⁵. Science ‘is not magic’⁴ or religion for that matter.

5.1.1.2. Instructional features that might influence NoS views. In general, students did not think that the current pre-laboratory provides them much insight into Nature of Science or if they get understanding of NoS from pre-lab^{2,3,4,5,6}, which was not surprising, as NoS was not made explicit in any of the pre-laboratory activities or resources. One conceded that he ‘never had any thought beyond the experiment’³, whereas another one said that ‘[t]he idea of science ... [was] not something that [she] really spen[t] much time thinking about’⁶ during the learning continuum of laboratory. One student explained why this was the case,

‘You can never know everything. So sometimes when I read the manual, I can get slightly caught up in those details rather than focussing on just accomplishing what I need to accomplish.’⁵

Notwithstanding the initial lack of reference to NoS in pre-laboratory, a student maintained that pre-laboratory videos gave a hint of how science works⁴. Another

student asserted, '[i]n terms of how science works, partly, [the pre-laboratory videos] definitely addressed the best experimental procedure, ... [they] often speak of reliability [and] accuracy of results'³. Students tend to think that the pre-laboratory videos focus more on experimental aspects^{2,4}. The part on theory is usually not in-depth, but it encourages them to think about 'why [they] are doing it'¹.

Interestingly, students believed that report-writing provided them with opportunities for thinking more about science and the chemistry behind the experiment they have done. One described,

'I think report writing is interesting because in phys[ical] chem[istry], ... you have to do your own reading. It's not like in organic chemistry experiment where you [are given a prescriptive instruction of] ... what happened. [In this laboratory] you have to look into it, understand it, ... It gives you thinking about what's happening, what you're doing makes sense.'²

Time constraints during the experiment in the laboratory is believed to be much less of a problem during the write up process, as one student maintained, 'there's a lot of independent study that we had to do quite long [during the report writing] and you have to understand what's going on. So that's a good place to start investigating. You have to find out sources and not always stuff you've been told in lectures ... to be able to back up what you've found'¹.

5.1.1.3. Wider context of laboratory education. An interesting, salient theme emerged from the discussion on Nature of Science, as students reflected on their experience as a student of an undergraduate chemistry programme at this university. One compared different modules, whereas the other different years.

'I've done a range of modules, tried everything out, and the only module I really enjoyed ... learning ... was environmental chemistry, coz it was applicable. I could see how it was useful in society. ... It was explained how gases are in the environment, the toxicity of metals in the body. Once we learn difficult theory, it was relevant a thing, you could see it in the world around you. You could discuss it with people.'³

Relevance and real life application are recurring themes in the other parts of interviews^{2,3,6}, and social context of science is an aspect of NoS that could be made more explicit in pre-laboratory. It is a facet of chemistry that instils 'enthusiasm and interest'³, which is one of the main reasons why the students chose to do a degree in Chemistry in the first place. Another student compared the modules across the years,

'Phys[ical] chem[istry] in [the] first year was not very in depth. Lab was dissolving salts and measuring the temperature. [We had to] fill in the blank sheets, not lab report. ...

[W]hen you get to [the] second year, ... you step up, [and you had to write a] new type of lab reports. ... [Y]ou [had] to think about the actual physical chemistry of the experiment. [The] third year is kind of build on that, but ... quite similar to [the] second year. The only different is that we have to think about our own procedures ... The experiments are a bit more in depth, because you do 2 experiments over 6 weeks, whereas in 2nd year you did 6 experiments and each of them took a session.¹²

5.1.2. Phase 2: Evaluation

In the second year of research, an adjusted version of Views of Nature of Science (Lederman *et al.*, 2002) was administered to 3rd year students in the physical chemistry laboratory. The new two-part laboratory structure was taken into consideration in both data collection for this questionnaire and the student interviews. Informal conversations with students and demonstrators were conducted during an unstructured observation. Students were to complete the questionnaire whenever they had time in between their laboratory activities. Due to the open-ended nature of the questionnaire, a number of students were not able to finish it. The returned, completed questionnaires were analysed. Their views of NoS were evaluated in accordance with a criteria for the level of NoS understanding (see Table 7). This criteria is a simplified version of a more sophisticated judgement (informed by the critical review of literature to warrant validity) and nuanced assessment of their responses. During the data analysis and interpretation, students' responses were weighed carefully, compared to other aspects (principle of interdependency of NoS), and coded accordingly, in order to warrant reliability.

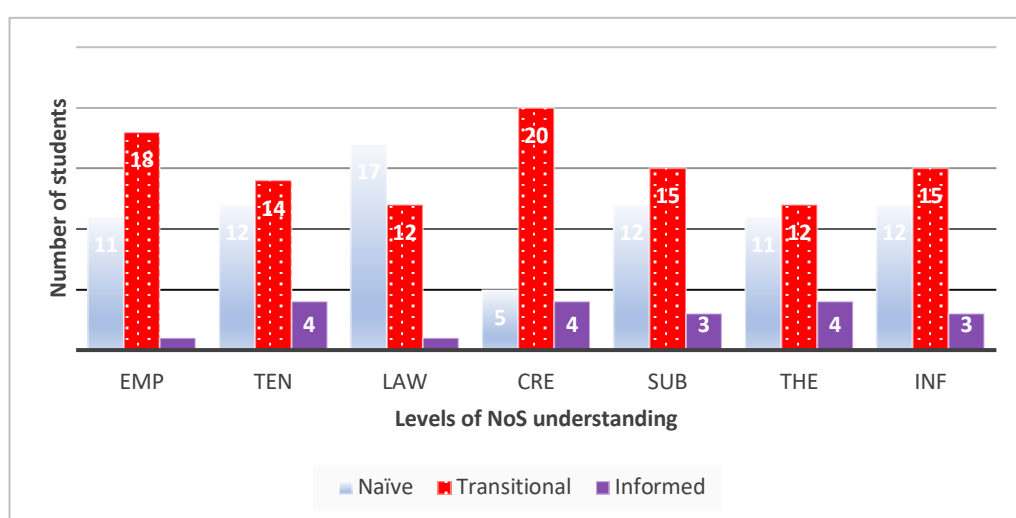
The evaluation was meant as a glimpse into the students' views of NoS at some point in their laboratory experience, rather than an assessment of any changes in their understanding. The rationale for this is, just like in the previous phases of the study (Pilot Phase and Phase 1), there was no intervention involved in this research. The new two-part structure of the laboratory was designed not in the context of this PhD, but rather the other way around, so the data collection followed this alteration in the way the laboratory instruction was designed and organised.

Data from both questionnaires and interviews were coded with NVivo. Each code was further mapped into the three levels of NoS understanding, *i.e.* naïve, transitional, and informed views. The following subsections are the findings from this evaluation

Table 7. Simplified criteria for evaluating students' level of NoS understanding

NoS Aspects	Level of understanding		
	Naïve	Transitional	Informed
Empirical and inferential nature of science	Focuses responses on only empirical evidence and has a particular focus on being able to see all aspects of what is being studied (even if it cannot be seen)	Understands that the atom is a model and that you cannot see it, but they are still overly focused on empirical data	Knows that inferences have to be made to create models, particularly about things that cannot be seen; knows that models are used to make additional inferences
Tentative nature of scientific knowledge	States that scientific theories do not change or thinks that scientific theories change because they are guesses or opinions	Acknowledges that scientific theories change, but the explanation is general or vague or there is no explanation	Understands that theories change and provides a reason and explanation as to why these changes occur
Scientific theories and laws	Subscribes to a positivist and static view of laws and theory and a hierarchical view between them	Has a tentative view of at least one of them but inadequate elaboration of their roles	Adequate understanding of the difference of their roles in science
Creativity and imagination in science	Says that scientists cannot be creative or cannot use imagination or says that they can use it only to fix bad experimental designs	Says that scientists use creativity and imagination but without elaboration	Creativity and imagination are needed throughout scientific process
Philosophical subjectivity and theory-ladenness	Indicates that coming to different conclusions from the same set of data would be because the data are bad or says that two scientists would not come to a different conclusion about the same data	Says that scientists can look at the same set of evidence and come up with different interpretations, but their explanation is overly simplistic or based on a perceived opinion of the scientist	Indicates that scientists can look at the same set of evidence and come up with different interpretations and provides a good explanation as to why
Social and cultural embeddedness	Believes that science is universal and devoid of any social and cultural influences	Mixed of universalist and contextualised view of science	Understands that science is contextualised in a larger social and cultural milieu

5.1.2.1. Questionnaire Data. Thirty students returned the VNoS-B questionnaires. Considering the open-ended nature of the instrument and the time frame in which they were administered, this was expected. It was also expected that most students would give a rather concise response to the seven statements. However, several participants went to great lengths to elaborate their views. Their written responses were analysed using the aforementioned criteria and mapped into a chart, as shown in Figure 18. An excerpt of data analysis is shown in Table 8, whereby levels of NoS understanding are represented by white (naïve), light grey (transitional), and grey (informed).



NoS Aspects: EMP = Experimentation and empirical nature of science; TEN = Tentative nature of scientific knowledge; LAW = Scientific theories and laws; CRE = Creativity and imagination in science; SUB = Philosophical subjectivity; THE = Theory-ladenness; INF = Observation and inference in science

Figure 18. Students' levels of NoS understanding mapped from VNoS questionnaires

Table 8. Excerpt of questionnaire data analysis, whereby levels of NoS understanding are represented by white (naïve), light grey (transitional), and grey (informed)

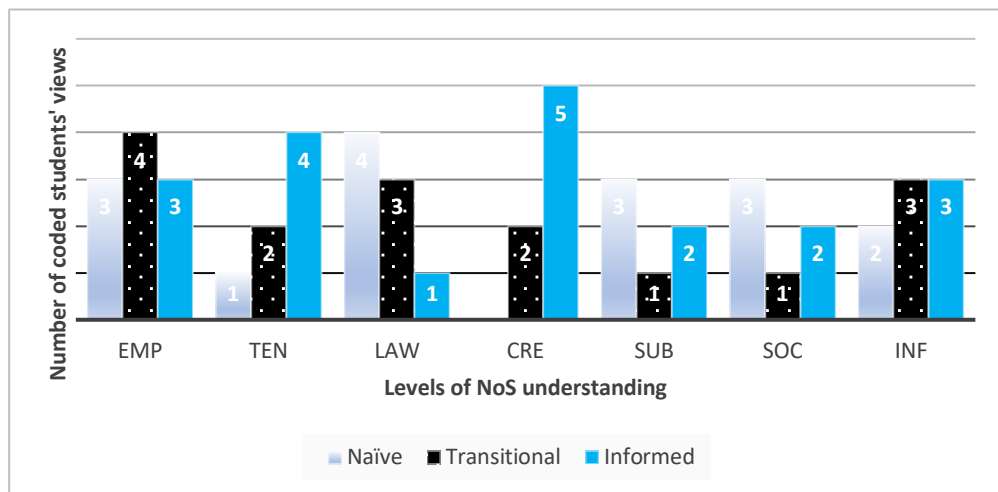
ID	Tentativeness of knowledge	Inferential nature of science	Scientific theories & laws	Empirical nature of science	Creativity & imagination in science	Subjectivity in science	Theory-ladenness
1	Yes it is tested in many ways to see if the theory holds up and that there are no exceptions. If exceptions arise, the theory is revised to accommodate these exceptions – and repeat.	I'm sure some scientists are sure by the use of quantum mechanics although I feel as quantum mechanics is a difficult field to draw conclusions of, the structure of the atom is nowhere near as defined as it could, and will be.	Theory is for building laws upon – the theory cannot really be proven wrong or right without an accompanying law. $V=ik$ is a classic law that holds up to scrutiny, whereas the theory of relativity was controversial and unsure until proof was given, backing up that theory.	Similarities can be drawn. Maths, as the science of number can be linked to all of music, a form of art, and how we interpret musical rhythm, harmony and melody. Music is just varying rations of vibrational waves which our ears understand very accurately in rations such as 2:1 (octave), 3:2 (fifth) if the freq is 20-20,000 Hz.	I guess they use some creativity and imagination as some scientists find very useful new techniques to analyse data although a lot of it is just following tried and true techniques of data analysis – not saying this is much different to art as that happens very often, there two-linking the two subjects again.	Science is based on facts, but I feel science is a growing subject where facts are in place as scaffolding therefore it should be encouraged to test the boundaries of what known are facts, therefore people should have an opinion on what scientific knowledge is just scaffolding for a bigger idea.	NA
4	Yes.	As certain as they can be given current limitations of tech and theory. Never 100% certain as you don't know how far things will advance in future.	Yes – laws are set and can't be disproved, theories are never completely set otherwise they would become laws. Theories are based on laws.	They are both creative for people at the top of their profession. In general science is more fact based whereas art is often more subjective. Science can be used in the explanation of art but art is not used in the explication of science.	Not so much during as you should just be following the experiment/inv estigation you've designed. Fore sure after data collection.	Scientific knowledge is a widely regarded opinion. Not all opinions are scientific fact and knowledge lies somewhere in between.	Different theories, based off different knowledge, based of different opinions.
5	Yes a theory can always develop to a greater extent with the passage of time.	They are certain about the components found in an atom but not how they are arranged.	Yes the difference is that theories are often based on laws.	Both science and art have progressed when original ideas are introduced in the respective field.	Yes when analysing data and observing new trends.	Scientific knowledge is a highly accepted scientific opinion.	Data can be interpreted in different ways if conclusion made are based on different theories.
8	Yes, it can change if evidence is provided to either disprove and therefore change or further prove science is always changing.	Pretty certain as there is strong experimental evidence to support it. However there is no saying whether more evidence will come along and change it.	A scientific law shows what is happening in the form of a formula such as $E=mc^2$. A scientific theory explains what is happening. An example of this is molecular orbital theory.	Science and art are similar in the way they are creative and they aim to understand the world we live in. They are different in the methods they use and in the people they attract.	Interpreting data and presenting it within a lab report can be seen as using creativity and imagination.	Yes, as a person can have scientific knowledge and no scientific opinion and vice versa.	The way a scientist interprets data can be completely different to the way another scientist does, therefore reaching different conclusions.

5.1.2.2. Interview Data. Akin to the previous cycles of data collection, students' interview responses were transcribed verbatim. The interview transcript from the evaluative phase amounted to approximately 14,000 words. To get a general impression of what was mostly referred to during the interviews, word frequency query was run on responses from interviewees' 9 to 14 (Table 9).

Table 9. Word frequency query of the interviews on the nature of science (excerpt)

Word	Count	Weight (%)	Similar Words
think	324	3.89	believe, believed, consider, considered, considering, guess, imagination, imagine, imagining, intelligible, mean, means, reason, reasonable, reasonably, reasons, recall, remember, suppose, supposed, supposedly, think, thinking, thinks, thought, thoughts
theory	146	2.10	hypothesis, possibilities, possibility, possible, theories, theory, theory'
science	122	1.85	science, skills
experiment	138	1.55	experience, experiment, experimental, experiments, feel, feels, getting, know, knowing, lived, living, seeing
knowledge	100	0.99	know, knowing, knowledge, knowledgeable, learn, learning
make	118	0.98	build, caused, causes, clear, construct, create, creating, draw, established, form, gain, getting, give, hitting, hold, make, makes, making, name, names, prepare, pretending, produce, produced, reached, realise, take, takes, taking, work, worked, working, works
sure	65	0.97	author, certain, certainly, confident, sure, surely, trusted
change	58	0.88	change, changed, changes, changing, modify, shifts
example	65	0.86	case, cases, example, examples, illustrate, model, represent
opinion	75	0.72	belief, beliefs, feel, feels, notion, opinion, opinionated, opinions, rules, thought, thoughts, view, views
find	78	0.69	breakthrough, detect, determine, discover, discovering, discovery, feel, feels, find, finding, findings, finds, getting, happen, happened, happening, happens, noticed, observation, observations, observe, obtaining, rules, seeing, witnessing
right	94	0.66	correct, correctly, good, laws, power, powerful, properly, right, true
evidence	78	0.65	demonstrator, demonstrators, evidence, observation, observations, observe, obviously, prove, proves, show, showed, tell, telling, tells
data	42	0.64	data, information
scientific	37	0.57	scientific
development	45	0.56	break, develop, developed, developing, development, developments, develops, evolution, evolve, evolving, formulate, getting, growing, prepare, produce, produced, rise, training
scientists	35	0.54	scientist, scientists
understand	53	0.53	agreement, agreements, clear, intelligible, interpret, interpretation, interpreting, read, realise, reason, reasonable, reasonably, reasons, seeing, understand, understanding

Each code extracted from the data was further mapped into three levels of NoS understanding, *i.e.* naïve, transitional, and informed views, referring to previous studies on NoS assessments, as shown in Figure 19.



NoS Aspects: EMP = Experimentation and empirical nature of science; TEN = Tentative nature of scientific knowledge; LAW = Scientific theories and laws; CRE = Creativity and imagination in science; SUB = Philosophical subjectivity; SOC = Social and cultural embeddedness; INF = Observation and inference in science

Figure 19. Students' level of NoS understanding mapped from the interviews

5.1.2.2.1. Experimentation and empirical nature of science. Several responses coded from three students^{11,12,13} views on experimentation and empirical NoS are considered naïve. Other responses from four students^{9,11,12,13} fall into transitional category, and three others^{10,12,14} are considered informed views of this aspect.

Table 10. Excerpt of data analysis: *Experimentation & empirical nature of science*

Quotes and codes (in bold)	Analysis	Level
Files\\Interview Data\\Interview 3.13 Reference 1: 1.10% coverage I think theory from science is always proven by experiments or something happens from nature. We have to show with our data or result, we have to prove it .	Experiments are not conducted to prove theories but support them.	N
Files\\Interview Data\\Interview 3.11 Reference 3: 1.56% coverage Obviously they are quite different, because ... science is very strict and you try to find the truth and art is about your own truth and what you want to communicate and the reaction you want people to have looking at your art, and there's not much freedom in science . There's only like one answer we have to find out	A reference to 'the one and only truth' in science is naïve. A view of science as a strict, rigid entity is ill-informed and misled.	N
Files\\Interview Data\\Interview 3.12 Reference 1: 1.11% coverage Science is based on evidence and it can be tested over and over . And the same result comes out. It's a direct reflection of materials , states. It can't be rationally argued against , because of the evidence. So that's the main difference between physics and metaphysics.	Proper reference to the empirical base of science but still a rather naïve understanding of the infallibility of science.	T
Files\\Interview Data\\Interview 3.10 Reference 1: 1.77% coverage ... if you have ... this new reaction that doesn't conform to the [accepted] mechanism, ... you can use this understanding from the old theory to understand why that reaction doesn't conform, or maybe you can propose an explanation into why it doesn't work and make a new theory , or new mechanism.	Adequate argument, example, and elaboration.	I
Files\\Interview Data\\Interview 3.14 Reference 1: 4.05% coverage There are different ways of knowing , and religion is one of them. It's a matter of how we approach and justify knowledge . How we form our thoughts and conclude that specific field. [A proper example is given] Because in science you have someone else , ... you can reproduce it in a way that you can verify what others have done. In religion you can't necessarily produce the same result.	Adequate argument and elaboration.	I

5.1.2.2.2. Tentative nature of scientific knowledge. Several responses coded from one student's¹¹ views on tentative nature of science are considered naïve. Other responses from two students^{9,10} fall into transitional category, and four others^{9,10,13,14} are considered informed views of this aspect.

Table 11. Excerpt of data analysis: *Tentative nature of scientific knowledge*

Quotes and codes (in bold)	Analysis	Level
Files\\Interview Data\\Interview 3.11 Reference 1: 1.44% coverage [T]here are paradigm shifts . Obviously it's not so common , because they do experiments and they think what they found is the truth . And then maybe there's something that they didn't look at, like it happened with physics for example, and everything changes . But I would say most of the knowledge we have is probably quite accurate .	Although there is a reference to paradigm shift, the explanation was incorrect. There is still mentions of "the truth". Also, together with the rest of responses and examples given, the NoS view is considered naïve.	N
Files\\Interview Data\\Interview 3.9 Reference 1: 0.12% coverage [Theories] changed until it's empirically correct . Reference 2: 0.32% coverage It's difficult to talk about the capital T, Truth, when you have some sort of incommensurability between the theories	Proper reference to Kuhn's principle of incommensurability and tentative nature of scientific theories, but there is also a reference to "the capital T, Truth".	T
Files\\Interview Data\\Interview 3.10 Reference 1: 2.17% coverage [M]ost theories eventually [changed] as the understanding progresses..., they might just become a new theory , might just evolve . The new theory might be used together with the old one. For example, we still use [valence bond theory] although we know there's some inherent mistake in it.	Adequate explanation of the development (and replacement) of theories and the use of them in a current context.	I
Files\\Interview Data\\Interview 3.13 Reference 1: 2.04% coverage I think theories always change ... People used to think that Earth was flat, but now we know that it's round. Since there's a lack of knowledge, even though science is much developed now, we still have to look forward. ... I think some people believe this one, but later on when there's a new discovery, this one is taken over by new theories .	Adequate explanation of the development (and replacement) of theories.	I
Files\\Interview Data\\Interview 3.9 Reference 2: 0.19% coverage In physics we went from Newtonian mechanics to Einsteinian mechanics Reference 6: 2.06% coverage [Q]uantum mechanics is not our final theory . There's still undeveloped issues and most of the things that chemists work with is approximation anyway. [It] isn't entirely consistent with relativity theory either. So one of them must be at least developing. I don't think we're at the end .	Adequate explanation of tentativeness of knowledge and approximation in science. The rest of the response (edited out here) also supports his view. Proper example and elaboration.	I

5.1.2.2.3. Scientific theories and laws. Several responses coded from four students^{10,12,13,14} views on scientific theories and laws are considered naïve. Other responses from three students^{10,11,14} fall into transitional category, and one other⁹ are considered informed views of this aspect.

Table 12. Excerpt of data analysis: *Scientific theories and laws*

Quotes and codes (in bold)	Analysis	Level
Files\\Interview Data\\Interview 3.10 Reference 4: 1.33% coverage I think there's a difference in that you don't really have to understand the theory as long as you know the law. So in that terms I think a law might be higher . For example there's more theories to explain the law. The most important thing is the actual law, not the theory , although the theory might help you understand more or expand.	A clear hierarchical view of scientific theories and law is considered naïve.	N
Files\\Interview Data\\Interview 3.13 Reference 1: 0.85% coverage As far as I know, I think law is never changing . So scientists can come up with a theory but this can be contradicted by another theory. But I think laws are like firm and set . Reference 2: 0.62% coverage [For example] thermodynamics law. It never changes ; it's permanent . I can come up with any theory and other people can say that's wrong.	Akin to theories, scientific laws are also subject to revision and change. Theories and laws just serve a different function in science.	N
Files\\Interview Data\\Interview 3.14 Reference 1: 1.44% coverage Scientific theory... it has been confirmed that it's working. At the same time, it's called theory because it doesn't explain everything. Just like molecular orbital theory. Theories are guidelines , in a sense. They predict that things usually go this way, but they're not fully perfect .	There's a merit to this elaboration, but his view on scientific law is still naïve.	T
Files\\Interview Data\\Interview 3.9 Reference 1: 0.58% coverage [L]aw is... sort of ill-defined... and somewhat misleading term, because we always have the association from legal things that laws govern. But maybe that's not exactly what we mean by laws in science . Reference 3: 0.85% coverage I would take some sort of Humian perspective in a sense that law is regularity as opposed to, I suppose, dispositionalism , things are and do act in a certain way. I think it's difficult to really be satisfied with either explanation. Reference 4: 1.33% coverage [Theory] is definitely not the same [as it] describes more of an overall framework , whereas laws might be something that underlies the theory So just how we employ the term rather than... we talk about N-O theory rather than molecular laws. Laws are underlying things we employ to something like thermodynamics.	A rather sophisticated elaboration on what scientific law is, making a reference to philosophy (David Humes's school of thought, referred to here as Humian perspective)	I

5.1.2.2.4. Creativity and imagination in science. There is no naïve view on this aspect. Several responses coded from two students^{12,13} are considered transitional. Other responses from five students^{9,10,11,13,14} are informed views.

Table 13. Excerpt of data analysis: *Creativity and imagination in science*

Quotes and codes (in bold)	Analysis	Level
Files\\Interview Data\\Interview 3.12 Reference 1: 2.15% coverage <p>You use your imagination to come up with the solutions. I think if you have to come up with new theories, using your imagination.... I think all these great scientists like Einstein or Stephen Hawking, they were supposed to be good at using creativity and imagination. H: What about practising scientists in general? 12: I don't think so. I don't know. Maybe I'm wrong. I'd like to be wrong, but I really don't think so.</p>	<p>True, but the explanation falls short. Not only prominent, high-profile scientists use creativity and imagination. Students doing science, are in fact, also creative and imaginative to different extents.</p>	T
Files\\Interview Data\\Interview 3.10 Reference 1: 1.29% coverage <p>They probably have to be creative in order to explain data, for example the data was not expected, which very often happens for various reasons.</p> Reference 2: 0.85% coverage <p>During the data collection, I think they still have to be creative, for example in order to figure out ways how to arrange an experiment so that there's no air in the reaction vessel.</p> Reference 4: 1.07% coverage <p>If you're studying black holes and you don't know what happens when something enters the black hole. I'm sure there's a lot of imagination in thinking what might happen, when it's so far away and it's practically impossible to see what's happening.</p>	<p>Adequate argumentation and examples.</p>	I
Files\\Interview Data\\Interview 3.9 Reference 5: 0.68% coverage <p>Creativity is probably the more narrow concept, but even that... I would certainly say yes they do use, because even once you have your data, you still have to know what it tells you, what kind of analysis you have to do. That's the creative aspect of science.</p> Reference 6: 0.97% coverage <p>Imagination seems like the more fundamental concept. Imagining underlines all thought about something that's potential. [W]henver you plan to take something in a certain direction, or you have to do certain things with the data, or whatever, you use your imagination.</p>	<p>Adequate argumentation and examples.</p>	I

5.1.2.2.5. Philosophical subjectivity and theory-ladenness. Several responses coded from three students^{11,12,14} views on this NoS aspect are considered naïve. Other responses from one students⁹ fall into transitional category, and two other^{9,10} are considered informed views of this aspect.

Table 14. Excerpt of data analysis: *Subjectivity and theory-ladenness*

Quotes and codes (in bold)	Analysis	Level
Files\\Interview Data\\Interview 3.10 Reference 4: 1.33% coverage I think there's a difference in that you don't really have to understand the theory as long as you know the law. So in that terms I think a law might be higher . For example there's more theories to explain the law. The most important thing is the actual law, not the theory , although the theory might help you understand more or expand.	A clear hierarchical view of scientific theories and law is considered naïve.	N
Files\\Interview Data\\Interview 3.9 Reference 1: 1.23% coverage [Art] doesn't make a claim quite exactly or unfalsifiable in the way that science usually does. So in that way it would be odd to ask an artist to say, oh... how's your painting falsifiable? How can I say that this is objectively true? Reference 2: 0.83% coverage [O]nce you ... conclusively show something, you can't dispute it anymore . So once you conduct experiments that no one can reasonably object to, you can't claim both things anymore.	Akin to theories, scientific laws are also subject to revision and change. Theories and laws just serve a different function in science.	T
Files\\Interview Data\\Interview 3.9 Reference 1: 1.15% coverage Another challenge is the values that underlie your theory choice. So what kind of theory do we employ ... has to be linked to subjectivity. Because we want our theory to be internally and externally consistent . We want them to be as simple as possible. Those are the things that you can link to this objectivity. But that's also being challenged in that some people say maybe we should be ontologically diverse .	Very thoughtful and balanced argument, drawing some reference to the philosophy of science. This is a sophisticated view of philosophical subjectivity and theory-ladenness.	I
Files\\Interview Data\\Interview 3.10 Reference 1: 0.97% coverage I mean it's possible that the data can be explained by two theories . I'm not sure which one would be the more true one, but they might both be equally valid , given the data, whereas some geological features might be explained by both theories. Reference 2: 2.00% coverage I'm sure there's uncertainty in dating of the data where it might be unsure when the last dinosaur actually lived, where the data is limited, given the fossils. And I'm sure ... not all researchers working on that have all the data available . They might be just focusing on some.	Proper reference to philosophical subjectivity and adequate argumentation and examples.	I

5.1.2.2.6. Social and cultural embeddedness. Several responses coded from three students^{11,12,13} views on this NoS aspect are considered naïve. Other responses from one students¹⁰ fall into transitional category, and two other^{9,14} are considered informed views of this aspect.

Table 15. Excerpt of data analysis: *Social and cultural embeddedness*

Quotes and codes (in bold)	Analysis	Level
Files\\Interview Data\\Interview 3.11 Reference 1: 1.45% coverage I would say it's universal , because it's based on evidence , not just some thoughts and opinions. So when you talk about evidence, evidence is just the same regardless of your cultural upbringing or religion or whatever, and that's why scientists from all over the world can collaborate to work on the same thing. Because it's not a social science, it is universal.	A universalist view of science is considered naïve.	N
Files\\Interview Data\\Interview 3.12 Reference 1: 1.01% coverage I think it should be universal . Religion is more infused with social and cultural values. I think science deviates from that. It can be more trusted in telling the truth, because the truth is sometimes different from social and cultural values.	A universalist and absolutist view of science is considered naïve.	N
Files\\Interview Data\\Interview 3.10 Reference 4: 2.02% coverage That could definitely reflect that science in a heavily religious country might be different from an atheist country. Or when research is taboo from some other reasons. For example, the research on ... artificial insemination might be discouraged in religious countries. I'm sure there are more examples. But it depends on the subject where some are more universal, some are more influenced by social factors .	Regardless of where it is conducted, science is always influenced by social and cultural values.	T
Files\\Interview Data\\Interview 3.14 Reference 1: 3.10% coverage Historically, we know that there were people who tried to twist science. For example, in 1930s someone claimed that one race was better than the other races, justified by the size of the skulls. Or, some data from 1970s that cannabis is a gateway to drugs. Let's make a war on drugs. Yes, we have uniform, universal facts, but it's how we shape them that matters.	Adequate view and proper examples.	I

5.1.2.2.7. Models and inference in science. Several responses coded from two students^{9,14} views on this NoS aspect are considered naïve. Other responses from three students^{10,13,14} fall into transitional category, and three other^{10,11,12} are considered informed views of models and inference in science.

Table 16. Excerpt of data analysis: *Models and inference in science*

Quotes and codes (in bold)	Analysis	Level
Files\\Interview Data\\Interview 3.14 Reference 1: 1.10% coverage We are certain about 60-70%, at the same time, we have Heisenberg certainty saying that we'll never know where an electron is. We can think of electrons as a cloud. The visualisation of orbitals is captured in one specific time, in this context.	Naïve reference to visualisation as a real structure of atom.	N
Files\\Interview Data\\Interview 3.13 Reference 1: 1.72% coverage I don't think we are very sure about it, because atom is literally very small. We can only come up with hypothesis or theories . Since it's very small and they're like unknown world, I don't think scientists are very sure. They are trying to discover more about it, but I think there should be more to atomic theory. We still have more to discover.	Proper reference to uncertainty but inadequate explanation.	T
Files\\Interview Data\\Interview 3.12 Reference 1: 3.83% coverage We are at a certain level of certainty [about the structure of atoms], but that scale could be to an infinity. I don't think [we will ever have 100% certainty]. Because from a philosophical point of view, ... we could be more accurate in our description of what the things look like but I don't think we'll ever get an objective feel of what it really is. So, the representation of an atom is a way of looking at an atom and the image that I have of you is a way that I can look at you. But in both ways, there's a lot of inaccuracies there. I don't think I can ever get 100% accurate view of anything. Even like a bottle or anything.	Adequate description of inference about the structure of atom and the level of certainty about it.	I
Files\\Interview Data\\Interview 3.11 Reference 1: 2.16% coverage I think we have a good knowledge today, but I also think that it's so abstract and complicated that you can't just teach it to high school kids. You have to sort of give them an easier thing to represent it. But obviously you can go into physics and study it from a different perspective and it's just not a little ball with a nucleus and electrons spinning around it. I think it's just a way to... coz like human finds it easier to visualise things. So even for me, for example, it's easier to think about it that way than some abstract quantum mechanics.	Proper explanation of the function of inference and balanced view of the certainty level.	I

5.2. Dimension 2: Nature of Science in the Chemistry Laboratory

For the purpose of aligning this study with the gaps of knowledge and needs from practice indicated in the literature, a systematic review of empirical studies in the area of the nature of science was conducted (see the abstract in the Appendix, Article 6). In this review, 73 empirical studies were analysed in order to establish a case for pedagogical and philosophical validation of undergraduate laboratory curricula, by inquiring into multifarious research designs and instruments used to investigate its many dimensions, its representations in the literature, and pedagogical frameworks underpinning its approaches. In the following subsection, I will discuss some of the findings from the review, followed by a discussion on findings from this study, with regards to the nature of science in the laboratory.

5.2.1. Representation of NoS in Laboratory Education

As an integral part of science education, the laboratory has a distinctive pedagogy that characterises learning in its premises. Laboratory education is in itself a specific research area on which the corpus of literature is growing. Four decades of literature in pre-laboratory work have been reviewed elsewhere (Agustian & Seery, 2017). Therein a pedagogical framework to support learning in a complex environment such as the chemistry laboratory has been proposed, by means of scaffolding and providing information in advance of a complex learning scenario. Correspondingly, the paramount importance of designing pre-laboratory activities that (a) are embedded into the overall laboratory learning process; (b) focus on the whole task, overall strategy and approaches; (c) provide supportive information; and (d) address the affective domain has been reasserted. The guidelines were intended to be applicable to any type of strategy for effective learning in the laboratory.

Although not always stated in laboratory manuals or science textbooks (Abd-El-Khalick *et al.*, 2008; Hegarty, 1978), the understanding of NoS has actually been recognised as one of the five broad categories of laboratory objectives (Bates, 1978). In practice, however, it is not always made explicit. Principally, the systematic review is aimed at characterising a laboratory curriculum, particularly in undergraduate level, that is pedagogically as well as philosophically informed. Explication of NoS

aspects in the laboratory is arguably the first step toward pedagogical and philosophical validation of such curriculum.

Several pedagogical approaches to NoS instruction in the laboratory have been identified. Science teaching laboratory, especially at undergraduate level, seems to miss the NoS research development. This is described as follows. In terms of educational contexts in which NoS studies have been conducted, there is an almost equal divide between pre-college and college levels. Around 39 out of 73 publications are from the latter, 20 of which are in teacher education. Around 66% of the publications are in general science context, whereas 32% are in specific science disciplines such as chemistry and physics. There are 20 studies conducted in a laboratory context, which accounts for 27% of the entire publications. However, only seven studies focussed on science major undergraduate laboratories, *i.e.* four in biology (Bautista *et al.*, 2014; Hegarty, 1978; Saunders & Dickinson, 1979; Schussler *et al.*, 2013), two in chemistry (Russell & Weaver, 2008; Russell & Weaver, 2011); and one in physics (Caussarieu & Tiberghien, 2017).

Various educational interventions aimed at teaching students about NoS have been designed, implemented, and evaluated. Schussler *et al.* (2013) manipulated underlying laboratory pedagogy and NoS treatment in an introductory biology laboratory course and found that students' understanding of NoS was significantly affected by the intervention. Previously, Russell and Weaver (2011) compared three different laboratory curricula in an attempt to gauge the impact of those curricula on university students' understanding of NoS. The traditional verification laboratory was compared to inquiry-based and research-based laboratories. Their findings suggest that a research-based laboratory curriculum demonstrates the most learning gains in the understanding of NoS.

In terms of pedagogical frameworks for NoS in the laboratory, the following approaches, often used in combination, have been identified: inquiry-based pedagogies (16 studies), explicit, reflective pedagogies (7 studies), constructivist pedagogies (6 studies), authentic learning environment pedagogies (6 studies), learning continuum pedagogies (3 studies), and traditional pedagogies (8 studies). Inquiry-based pedagogies were the most common framework for teaching and studying NoS in the laboratory.

Accordingly, several inquiry-based pedagogical frameworks have been specified. For example, the activity model of inquiry has been found to facilitate students' understanding of NoS (Marchlewicz & Wink, 2011). This approach served as a thinking frame in which NoS aspects can be taught. Referring to Harwood (2004), this model identifies 10 activities in the course of inquiry, whereby scientist move among its unique paths as often as they find necessary, as shown previously in Figure 13. This model breaks the myth of *the* scientific method, which assumes that inquiry is a simplistic, linear method.

Constructivist pedagogies are also used in NoS studies in the laboratory. According to Vhurumuku (2011), the constructivist view of science entails an understanding that scientific knowledge is partly subjective, tentative, problematic, invented, and revisionary. Pomeroy (1993) categorises this view as non-traditional, as opposed to the traditional, largely positivist view. In their investigation into the impact of laboratory curriculum on students' understanding of NoS, Russell and Weaver (2011) found that there was little curricular impact at the surface level. Students in research-based laboratory, however, seemed to develop sophisticated conceptions and deeper understanding of NoS compared to students in traditional verification and inquiry-based laboratories. One of the determining factors in the success of this curriculum was the explication and explicitness of NoS in the laboratory pedagogy.

5.2.2. Students' Views and Understanding of Science

This study seeks to explore and evaluate undergraduate students' views of the nature of science in the context of the chemistry laboratory. In order to locate the study in an appropriate theoretical framework, arguments for laboratory education in undergraduate chemistry and the inclusion of the nature of science instruction in laboratory context were made. As a researcher, I am particularly interested in the pedagogical and philosophical validation of undergraduate laboratory curricula, which has been scarcely researched in the literature.

Initial findings revealed that in terms of students' understanding of the tentative nature of science, they seemed to subscribe to a dynamic view of scientific knowledge (Songer & Linn, 1991). In this view, ideas in science are regarded as

changing and developing entities and the best way to learn about them is to understand what they mean and how they relate to one another. Bell and Linn (2000) describe how this static *viz a viz* dynamic views of science influence students' learning strategies. Those who subscribe to the former tend to think that the best approach to learning science is by memorising facts and concepts (see also, Tsai, 1999), whereas those who subscribe to the latter tend to prefer understanding as the best approach.

The exploratory investigation into students' views of the tentative nature of scientific knowledge was substantiated further through the evaluative phase, using both versions of Views of Nature of Science (Form B and Form C). This phase also assessed other aspects of NoS, including the social and cultural embeddedness of science. Questionnaire results indicate that most students were on a transitional level of NoS understanding, for all aspects except scientific theories and laws, where they had naïve views. This was also indicated in the interviews. Naïve understanding of the difference between scientific theories and laws, their distinctive roles in science, and the non-hierarchical relationship between them, proved to be rather common among students. Similar to this result, Liang *et al.* (2006) found that the majority of students from the US, China, and Turkey believe that scientific laws are proven theories. The authors argue that informed views about this NoS aspect acknowledge that scientific theories and laws are merely two different types of knowledge, neither of which are certain.

Notwithstanding the predominantly transitional views among undergraduate chemistry students in this study, further investigation shows that there were more informed views captured by the interviews. With regards to creativity and imagination in science, there were roughly more than twice informed views than that of transitional views. None of the six students had naïve views of this aspect. A student posited, 'When you change a variable in an experiment and see how other variables are changing, you have to be creative enough to explain why it happens. Imagination is even more. You need to think of new breakthrough ways to see if a theory is wrong'¹⁴. Duschl and Grandy (2013) agree that understanding data is a complex and lengthy process. It requires considerable amount of ingenuity and creativity on the part of the scientists. Although scientists are sceptical of both data

and its interpretations, they can also resort to imagination and speculation to develop theories that might represent aspects of nature (Taber, 2017a). Echoing this, Bell *et al.* (2016) assert that creativity permeates all aspects of scientific investigations, from hypothesis generation to data interpretation.

The data also reveal that the profile of students' views of philosophical subjectivity and theory-ladenness in science mirror that of NoS in the context of the laboratory as a whole. The naïve views in relation to the transitional and informed views are roughly in proportion of 4:5:1. As previously stated, students' views of the nature of science in the context of laboratory are predominantly transitional. Bell *et al.* (2016) argue that scientific knowledge is influenced by theory that acts as a lens through which questions are developed, investigations are designed, decisions concerning data collection are made, and results are interpreted. When a new hypothesis is proposed, researchers try to assess its credibility by discussing the new theory in light of accessible empirical evidence and the massive network of existing established knowledge (Lunde *et al.*, 2016). These phenomena account for subjectivity in science. However, Matthews (2012) concedes that this conception can be ambiguous. Acknowledging that science is theory-laden is not equivalent to saying it is subjective in the everyday psychological meaning of the term. Matthews' critique on Lederman's research group's definition of this NoS aspect was resolved with what he coins as 'philosophical subjectivity', which is also adopted in this study. He argues further that the entire history of modern science is an effort to minimise the psychological subjectivity in measurement and explanation. A student maintains, 'the values that underlie [our] theory choice... [are] linked to subjectivity, ... [because] we want our theory to be internally and externally consistent'⁹.

Chapter Six. Conclusion

In this thesis, the undergraduate chemistry laboratory has been used as a context for study of students' learning experience and their views of the nature of science. A general introduction to this manuscript portrays how science education has failed and triumphed over the years. The urgency of evidence-based and research-informed science education has been argued. Narrowing down to undergraduate chemistry education, several issues pertaining to this context have also been exposed in Chapter 1, *i.e.* learning in the laboratory, pre-laboratory work, and the nature of science in the laboratory. The ultimate purpose of this research was to substantiate the need to address the pedagogical and philosophical validity of undergraduate chemistry laboratory curriculum. This purpose was translated into two main research questions, one concerning students' meaningful learning experience and the other addressing their understanding of the nature of science in the context of laboratory. In this chapter, key findings that directly correspond to these research questions will be summarised.

In Chapter 2, a comprehensive literature review of research development and intellectual discourse in the area of laboratory education and the nature of science was presented. Parts of this chapter laid a foundation for the writing and publication of review articles in its own. The first part of the review concerns the role of the laboratory in chemistry education, typology of laboratory curriculum and how students learn in various instructional designs, pedagogical frameworks for learning in the laboratory adopted in this study, multifarious aspects of pre-laboratory work, and assessments in the laboratory. The second part concerns research and development in the nature of science, arguments for incorporating NoS in laboratory education, redefinition of NoS for the context of this study, aspects of NoS investigated, and pedagogical goals and frameworks for NoS in the laboratory.

The methodology and methods used to address the research questions were presented in Chapter 3. In the beginning of the chapter, the positioning of this study in the intersection of research and practice was visualised. A rationale for emphasising the phenomenological element of this mixed methods research was also

justified. The remaining sections described the setting, some ethical considerations, and the research instruments used and measures taken to address each research question. I also described how data was collected and analysed.

In Chapter 4, I presented the results from data analysis, according to the methodology adopted in this study. Key emerging themes from the interviews were presented in accordance with the research questions. Some insights from the quantitative data analysis were also interpreted here. The findings from both exploratory and evaluative phases of the data analysis on the nature of science were reported accordingly.

The aforementioned findings were further discussed in Chapter 5. Two dimensions were particularly addressed, one concerning students' goals and expectations prior to the laboratory and the extent to which they benefit from pre-laboratory work, the other concerning representation of NoS in laboratory education, which results from the systematic review of research in this area, and students' level of understanding of science. Two sets of curricular guidelines were also proposed, to be used as a reference for laboratory curriculum designers.

In the following sections, key findings associated with the research questions will be summarised, limitations of the study will be depicted, and implications for research and practice will be presented.

6.1. Conclusion

Question 1: *“What are characteristics of students' meaningful learning experience in the undergraduate chemistry laboratory in relation to the pre-laboratory activities?”*

Students' learning experience in the laboratory is considered meaningful when it takes into account their cognitive, affective, and conative aspects of learning in an integrated, interconnected manner. With regards to pre-laboratory activities, findings from this study show that they facilitate higher order thinking skills through learning goal setting. The awareness of what they can accomplish in the laboratory by preparing for the lab sessions, the affordances to foresee the amount of information they have to manage, and the opportunity to familiarise themselves with new techniques or instruments prior to the actual performance, and the knowledge

of how they can go about the data (e.g., calculation and plotting), are some of the aspects pertinent to pre-laboratory work that seem to enhance students' learning experience in the laboratory.

Sub-question 1a: *"What are ways in which students prepare for their laboratory work?"*

In order to prepare for laboratory work, students used various combination of the available pre-laboratory resources and activities, including the online laboratory manual, pre-laboratory videos, online discussion forum, and supplementary articles. The pre-laboratory work helps them feel more confident during the experiment and data analysis.

Sub-question 1b: *"Which learning goals pertinent to the laboratory are prioritised by students?"*

At face value, students seem to emphasise practical goals related to the experiment they were going to conduct. However, further investigation demonstrates that they actually expect to learn about higher order cognitive skills, including critical thinking, problem solving, and making sense of data.

Sub-question 1c: *"How do students manage information during their laboratory work, in relation to the pre-laboratory activities?"*

Students use strategies to manage information during their laboratory work by chunking information in the form of pointers to consider, similar questions that are already answered on the online discussion forums, and by keeping an organised laboratory book so they can have a good overview of the amount of information they have to manage.

Sub-question 1d: *"To what extent does students' learning experience influence their affective domain?"*

In so far as affective domain is concerned, developing confidence in the laboratory is the most important goal set by the students in this study. In particular, pre-laboratory videos help them with this goal setting.

Question 2: *"To what extent do students understand the nature of science in the context of the undergraduate chemistry laboratory?"*

Results indicate that in the context of physical chemistry laboratory, most students have a transitional level of understanding of all NoS aspects except the

difference between scientific theories and laws, in which they have mostly naïve views. This aspect entails an understanding of the distinctive roles played by theories and laws in science and the non-hierarchical relationship between them. On the other hand, further investigation demonstrates that most students are well informed about creativity and imagination in science.

Sub-question 2a: *“What are students’ views of the nature of scientific knowledge?”*

Students seem to subscribe to a dynamic view of scientific knowledge, in which ideas in science are regarded as tentative, provisional, and developing entities. This view also entails that the best way to learn about science is to understand what they mean and how they relate to one another.

Sub-question 2b: *“To what extent does laboratory instructional features influence students’ views of NoS?”*

The data shows that the current laboratory instructional features have no direct influence on students’ views of the nature of science, at least, as far as reflective accounts of students participating in this study are concerned.

Sub-question 2c: *“What is the level of students’ understanding of the nature of science?”*

The overall proportion of the level of NoS understanding of the students in this study is 4:5:1 (naïve, transitional, informed views respectively). In general, students have a transitional level of sophistication in terms of NoS views.

6.2. Proposed Curricular Guidelines

Essentially, this study aims to inform practice in the context where it was conducted as well as undergraduate laboratory education at large. Having discerned salient themes from the lived experience of undergraduate students doing a course in physical chemistry laboratory, two sets of curricular guidelines will be proposed. The first set concerns pre-laboratory work and how it could be embedded in the laboratory curriculum in a more integrated manner, based on the evidence found in the study. The second set concerns the nature of science and how it could assume more presence in undergraduate chemistry laboratory education.

6.2.1. Guidelines for Incorporating Prelab into the Laboratory

The existing pre-laboratory activities are already viewed as beneficial for learning. It is the purpose of this project to fine-tune them so that they benefit the students even more. Based on the findings so far, there are a few pointers for future development of pre-laboratory, namely:

1. There has to be a coherent pedagogical framework in which pre-laboratory activities are designed. I strongly recommend the cognitive load theory and complex learning theory. They are compatible with each other and are well studied.
2. In terms of content, pre-laboratory activities should provide more insight into the application of knowledge or topic related to the experiment, in a pursuit of ever slightly higher order thinking. This could be done in the context of focussing on supportive information (Agustian & Seery, 2017).
3. The affective domain should be addressed more adequately from pre-laboratory stage on, by foreshadowing parts of the experiment that could be tricky and, therefore, cause frustration. Students need to be reminded that there are some motivational aspects of frustration whenever it happens.

6.2.2. Guidelines for Incorporating NoS into Laboratory Curriculum

In designing undergraduate laboratory curricula, priorities must be weighed and compromises may have to be made, but if student understanding of NoS is to be a major curriculum goal of science education, the following guidelines are worth considering:

1. More efforts should be made to promote explicit NoS instruction. The evidence for this approach is substantial. The ultimate goal for NoS teaching in the context of laboratory is for students to have informed views of the nature of science, so that overall learning gains from the laboratory can be increased.
2. Designing a course needs collaborative work between instructors and researchers to construct a conceptual framework. This design-based research approach will help instructors become aware of the necessity of refining and aligning their goals. Likewise, science education researchers ought to work together with philosophers of science in keeping with the contemporary

debates and discourse on both substantive and syntactical structures of science.

3. In addition to science content knowledge and skills, NoS should be continuously reinforced as an objective of science education at undergraduate level, so that the integral role of laboratory work in science disciplines could be more clearly perceived. In doing so, laboratory instructors are encouraged to collect perception data from their students in a dialogue concerning the role of laboratory in science and how their view of science could enhance the learning of scientific concepts and NoS.

6.3. Limitations of Study

Despite the efforts to substantiate students' lived learning experience in the laboratory, this study entails several limitations. Due to the small sample size (N=129 for quantitative analysis and N=14 for qualitative analysis), the results from this study cannot be generalised. Also, because they are highly contextualised in the educational setting in which the study was conducted, transferability instead of generalisability is presumably more appropriate. It was not my intention to sketch a general image or profile of chemistry students doing a course in laboratory, but to understand the context from which the need to investigate came in the first place. This study was exploratory by nature, to lay a foundation and direction for future research in laboratory education, especially with regards to interventionistic studies on the effect of modifications to pre-laboratory work and corresponding instructional designs.

With regards to the evaluation of students' level of understanding of the nature of science, the findings from this study are limited to the students participating in the data collection. Careful analysis was conducted and potential bias was minimised but eventually, the judgement of one researcher may not represent the whole. In an ideal phenomenological study, at least three researchers should be involved in the analysis and interpretation of one set of data, something that was impossible for this project. However, through continual critical discussions with the supervisor and occasionally with another researcher in this project, other perspectives were gathered and considered.

6.4. Implications

This study may have implications for both research and practice. Because the university chemistry laboratory has largely missed out on the research and intellectual development in the nature of science, this study could serve as an impetus for future studies on epistemological and ontological elements of learning in the chemistry laboratory. Useful directions to guide future research may include the development and validation of research instruments that build on Lederman's Views of Nature of Science, preferably with clearer assessment criteria. The statements used to evaluate students' understanding could also be updated and contextualised in university science education.

In terms of chemistry education practice, the findings from this study may be relevant for curriculum designers and course developers. The proposed curricular guidelines were meant to be used by practitioners who are interested in modifying their laboratory course to integrate more evidence-based and research-informed pedagogical framework. The element of philosophical validity that was strived for in this study could also be an essential point for consideration, as this is still scarce.

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Appendices

7.1. Appendix A. Student Questionnaire on Learning in the Laboratory

This questionnaire is a part of my PhD research in chemistry education, aimed at enhancing learning in laboratory. My name is Hendra Agustian and I am conducting this PhD under supervision of Dr Michael Seery. I have degrees in both chemistry and education. Prior to this PhD, I worked as a teacher, curriculum coordinator, and educational researcher in Indonesia and the Netherlands. If you have any concerns or questions related to this research, you can reach me at hendra.agustian@ed.ac.uk.

You will be asked to express your agreement on several statements regarding learning in the physical chemistry laboratory. There are no “right” or “wrong” answers. Your opinion is what is wanted. Think about how well each statement describes your learning experience. Whatever response you give here, it will not affect your marks.

Your participation in this research is important and highly appreciated. The data gathered from this questionnaire will only be used for the purpose of this PhD. Data protection and anonymity will be ensured. You have the right to withdraw at any point of this research.

By ticking this box, you agree to give your informed consent.

☐

Be sure to give an answer to all questions. If you change your mind about an answer, just cross it out and circle another. Some statements in this questionnaire are fairly similar to other statements. Don't worry about this. Simply give your opinion about all statements.

I am ☐ Male ☐ Female ☐ Other ☐ Prefer not to say

Which experiment are you going to do?

- ☐ Rotational-Vibrational Spectroscopy to determine molecular constants
- ☐ Flash Photolysis to study fast reactions
- ☐ Karl Fischer Titration to analyse water content
- ☐ Gas Chromatography for separation of hydrocarbons
- ☐ Clausius-Clapeyron Equation to determine enthalpy of vapourisation
- ☐ Kinetics of a second order reaction
- ☐ Factors affecting energy barriers for pyramidal inversion in amines and phosphines

Continued on the following page

On scale of 1 to 5, where 1 is strongly disagree and 5 strongly agree, how would you rate the following aspects of learning in this laboratory?

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
Preparation for laboratory					
1. I feel well prepared for this laboratory practical.	1	2	3	4	5
2. I understand the theory behind this experiment.	1	2	3	4	5
3. I understand why I have to do all steps in this experiment.	1	2	3	4	5
4. The pre-lab videos help with doing calculations for the lab.	1	2	3	4	5
5. I feel confident that I can do this experiment well.	1	2	3	4	5
Pre-lab videos					
6. The pre-lab videos help me understand the experiment that I am going to do.	1	2	3	4	5
7. The pre-lab videos prompt some questions about this experiment.	1	2	3	4	5
8. I know how I can go about those questions.	1	2	3	4	5
9. I learn the relevant skills needed for this experiment from the videos.	1	2	3	4	5
10. The pre-lab videos give me an idea about how science works.	1	2	3	4	5
11. The pre-lab videos motivate me to learn more about this topic.	1	2	3	4	5
12. The information I learn from the pre-lab videos help reduce the stress of dealing with too much information during the experiment.	1	2	3	4	5
The experiment					
13. This experiment is interesting.	1	2	3	4	5
14. I enjoy doing this experiment.	1	2	3	4	5
15. I can understand the chemistry in this topic by doing the experiment.	1	2	3	4	5
16. I am confident enough with the laboratory techniques to be able to concentrate on the chemistry involved in the experiment.	1	2	3	4	5
17. I feel that I can manage the amount of information that I have to deal with during the experiment.	1	2	3	4	5

18. I can distinguish important information from background information during lab.	1	2	3	4	5
19. When doing the experiment, I try to understand the theory behind the experiment.	1	2	3	4	5
20. I look for justifications and evidence to make my own conclusions about things to be learnt in the experiment.	1	2	3	4	5

After the laboratory session

21. After the lab session, I reflect on the experiment that I have done.	1	2	3	4	5
22. I search and read additional material concerning the experiment.	1	2	3	4	5
23. I can write up my lab report well.	1	2	3	4	5
24. I feel that pre-lab helps me understand what I write in my report.	1	2	3	4	5

7.2. Appendix B. Views of Nature of Science – Form B

Student number: _____

Views of Nature of Science

This questionnaire is a part of my PhD research in chemistry education, aimed at enhancing learning in laboratory. My name is Hendra Agustian and I am conducting this PhD under supervision of Dr Michael Seery. I have degrees in both chemistry and education. Prior to this PhD, I worked as a teacher, curriculum coordinator, and educational researcher in Indonesia and the Netherlands. If you have any concerns or questions related to this research, you can reach me at hendra.agustian@ed.ac.uk.

You will be asked to respond to a few questions on your views of science. There are no “right” or “wrong” answers. Your opinion is what is wanted. Whatever response you give here, it will not affect your marks.

Your participation in this research is important and highly appreciated. The data gathered from this questionnaire will only be used for the purpose of this PhD. Data protection and confidentiality will be ensured. You have the right to withdraw at any point of this research.

By ticking this box, you agree to give your informed consent.

☐

Be sure to give an answer to all questions. If you need more space for your responses, kindly use the space available on Page 2. Simply give your opinion about all statements.

1. After scientists have developed a theory (e.g. atomic theory), does the theory ever change?

2. How certain are scientists about the structure of the atom?

3. Is there a difference between a scientific theory and a scientific law? Give an example to illustrate your answer.

4. How are science and art similar? How are they different?

5. Other than designing experiments/investigations, do scientists use their creativity and imagination during and after data collection?

6. Is there a difference between scientific knowledge and opinion?

7. Some astronomers believe that the universe is expanding while others believe that it is shrinking. How are these different conclusions possible if all of these scientists are looking at the same experiments and data?

7.3. Appendix C. Interview Protocols

7.3.1. Pilot and main phases

Do you mind if I record our conversation?

This interview will be strictly confidential. Only I will hear it. We may publish text excerpts of what you say, but we will make sure that it is anonymous.

Pre-laboratory

1. What were you hoping to accomplish in lab yesterday? OR What were you hoping to accomplish in lab earlier today? Which experiment did you do?
2. How did you prepare for that lab session?
3. What do you think about the pre-lab activities and resources related to this experiment? What are they? Which one do you think is most effective in promoting your learning? Why?
4. What do you think is good about the pre-lab videos? Specify part of the videos that you think is most effective in promoting your learning. What would you suggest if they were to be modified?
5. What could you have done differently to prepare better for the lab?
6. What do the videos tell you about science in general and how it works?

Nature of Science

Typically, the Nature of Science (NoS) has been used to refer to science as a way of knowing, or the values and beliefs inherent to the development of scientific knowledge. It also refers to one's understanding about the social practices and organization of science and how scientists collect, interpret, and use data to guide further research.

I would like to know your beliefs/views on the following statements and/or questions. This is not about right or wrong responses however you need to respond with more than just yes or no offering supporting statements and examples.

7. Some scientists believe that explanations of chemical phenomena, such as atomic theory, are accurate and true descriptions of atomic structure. Other scientists say that we cannot know whether or not these theories are accurate and true, but that scientists can only use such theories as working models to explain what is observed.

What do you think about this statement? How did you come to hold that point of view or answer? On what do you base that point of view or answer?

8. What **instructional feature** (pre-lab, laboratory work, or post-lab), if at all do you believe influenced your beliefs about the **Nature of Science** in this course?
9. How do you think **pre-laboratory activities**, if at all, inform your views of Nature of Science BEFORE you start your lab session?

Information management

10. How were you feeling when you were doing the experiment? In scale of 1 to 10, how would you rate your level of confidence in lab? Elaborate.
11. How did you manage the amount of information during the experiment? Why did you do that?
12. What do you think about the chemistry behind the experiment you have done? Have you learnt any of that from the pre-lab? Please specify.
13. Can you please tell me what you think you accomplished during lab?
14. Do you have any questions for me?

7.3.2. Second phase

Main research questions of the 2nd phase:

- *What is the extent to which students benefit from the first part of laboratory to prepare for the second part (investigation) in the physical chemistry laboratory?*
- *Which pedagogical activities related to laboratory (pre-laboratory, in-laboratory, post-laboratory) do students believe were essential to their understanding of NoS (in Chemistry) during the physical chemistry laboratory experience?*

Do you mind if I record our conversation?

This interview will be strictly confidential. Only I will hear it. We may publish text excerpts of what you say, but we will make sure that it is anonymous.

1. Two-part laboratory structure

1.1 Tell me about the most recent experiment you did.

1.2 In your opinion, how were the two parts of lab different? In which way?

1.3 How did you experience both parts? What kind of challenges did you face?
Which strategies did you use to manage those challenges?

1.4 Can you recall specific examples of how you used the experience of the first part to help you do the second part? Elaborate.

1.5 What could you do to improve your experience in the second part of the experiment?

2. Nature of Science

Typically, the Nature of Science (NoS) has been used to refer to science as a way of knowing, or the values and beliefs inherent to the development of scientific knowledge. It also refers to one's understanding about the social practices and organization of science and how scientists collect, interpret, and use data to guide further research.

2.1 There are many differing views or images of the nature of science and scientific knowledge. I would like your views on the following statements:

2.1.1 After scientists have developed a theory (e.g. atomic theory), does the theory ever change?

2.1.2 How certain are scientists about the structure of the atom?

- 2.1.3 Is there a difference between a scientific theory and a scientific law? Give an example to illustrate your answer.
- 2.1.4 How are science and art similar? How are they different?
- 2.1.5 Other than designing experiments/investigations, do scientists use their creativity and imagination during and after data collection?
- 2.1.6 Is there a difference between scientific knowledge and opinion?
- 2.1.7 Some astronomers believe that the universe is expanding while others believe that it is shrinking. How are these different conclusions possible if all of these scientists are looking at the same experiments and data?
- 2.2 To assess perceived changes in your views of NoS related to laboratory instruction and corresponding attributes, you are asked to elaborate your views of the nature of science in relation to laboratory instruction.
- 2.2.1 How, if at all, has the laboratory experience influenced your views on NoS?
- 2.2.2 Do you think your view or understanding has changed? To what do you attribute the change? (Or, if there was no change) Why do you think the view was stable?
- 2.2.3 Consider the laboratory instructional experience, the pre-laboratory activities (manual, videos, online discussion board), the laboratory notebooks, and other instructional sessions. Do you think any of these components of the laboratory influenced your views of NoS? If so, what components? How? And Why?
- 2.2.4 Can you recall examples or specific instances that you feel had an influence on your understanding? Explain.

7.4. Appendix D. Phenomenological Data Analysis Method

Step 1

H: With regards to your most recent experiment, what were you hoping to accomplish?

2: So the aim was to **determine the relaxation time caffeine**, to **learn how to use the benched up NMR machine**. For part 1 we also used NMR to **determine the peaky A (?)**, isoelectric point of the **amino acid**.

Step 2 and 3

[<Internals\\Interview Data\\Interview 1>](#) - § 1 reference [coded](#) [0.21% Coverage]

Reference 1 - 0.21% Coverage

I tried to **get as much done as possible**

[<Internals\\Interview Data\\Interview 2>](#) - § 3 references [coded](#) [0.54% Coverage]

Reference 1 - 0.16% Coverage

the aim was to **determine the relaxation time** of caffeine

Reference 2 - 0.14% Coverage

to **learn how to use the benched up NMR machine**

Reference 3 - 0.24% Coverage

we also used NMR to **determine the peaky A (?)**, isoelectric point of the **amino acid**

Step 4

Prelab	Personal goals
	<Internals\\Interview Data\\Interview 1> - § 1 reference coded [0.21% Coverage] Reference 1 - 0.21% Coverage I tried to get as much done as possible <Internals\\Interview Data\\Interview 2> - § 3 references coded [0.54% Coverage] Reference 1 - 0.16% Coverage the aim was to determine the relaxation time of caffeine

Step 5

Other students were more pragmatic and focussed on their personal goals, as they mainly just hoped to 'finish part 2' of an experiment^{4,5,6} and 'get as much done as possible'^{1,a}. Having finished part 2 of a computational experiment, which incorporated investigation aspects, a student hoped 'to make sense' of the data that she had obtained in the first, prescribed part⁴.

Step 6

Prelaboratory

The data analysis on NVivo generates the following tree map (Figure XXX). The colour represents the number of items coded. As Figure XXX suggests, much of the discussion during the interview centred around pre-laboratory videos, which was also the focus of the previous data collection in the first year of this research project.



Figure XXX. Tree map of pre-laboratory section

Step 7

Goals and expectations. Before commencing a laboratory work, students have their own goals and expectations. This may reflect the goals set by the laboratory course designer, as written in the laboratory manual. A student set the goal to 'determine the relaxation time of caffeine' and 'learn how to use the benchtop NMR spectrometer'², whereas another aimed to 'determine the second order rate coefficient' by using 'UV 1800 spectrometer to measure absorbance'³.

7.5. Appendix E. NVivo Coding

Table 17. Coding on NVivo (pilot & main phases)

Interview Data			
Name	Files	References	
Pilot & main phases	0	0	
1. Prelab	0	0	
1. Personal goals	6	13	
2. Preparing for lab	5	28	
Better prepared next time	5	10	
3. Prelab work	6	25	
Most effective prelab	5	13	
4. Prelab videos	6	31	
Most effective part to promote learning	5	8	
Suggestion for modification	5	14	
Videos & NOS	5	14	
2. NOS	0	0	
1. View on NOS	5	11	
Argument	5	12	
Context of chemistry course	2	10	
2. Instructional feature influencing NOS	5	6	

Interview Data			
Name	Files	References	
3. Prelab activities informing NOS prior to lab	3	4	
3. Information management	2	4	
1. Managing information	4	8	
2. Chemistry behind the experiment	5	8	
Relevance of prelab	1	4	
Synchronous lecture and lab	1	2	
Self assessing the accomplishment	4	9	
4. Affective domain	2	9	
1. Feeling during experiment	6	13	
2. Level of confidence	5	11	
Challenges in the lab	5	7	
Demonstrator's role	9	12	
Postlab	3	6	

Table 18. Coding on NVivo (2nd phase)

Interview Data			
Name	Files	References	
Second phase		0	0
2-part laboratory structure		3	12
Recommendations		1	2
Strategies to cope with challenges		1	1
NOS in laboratory		6	18
Cookbook experiment		1	2
Organic chemistry laboratory		2	3
Physical chemistry laboratory		1	1
Prelab & NOS		5	5
VNOS		0	0
1. Empirical nature of scientific knowledge		1	1
1.1. Naive		3	11
1.2. Transitional		4	9
1.3. Informed		3	10
2. Inference, observation & theoretical entities in		0	0
2.1. Naive		2	2
2.2. Transitional		4	4

Interview Data			
Name	Files	References	
3. Tentative nature of scientific theories		0	0
3.1. Naive		1	4
3.2. Transitional		2	3
3.3. Informed		4	13
4. Scientific theories vs scientific laws		0	0
4.1. Naive		3	8
4.2. Transitional		4	5
4.3. Informed		2	5
5. Creativity and imagination in science		1	2
5.1 Naive		0	0
5.2. Transitional		2	3
5.3. Informed		5	17
6. Subjectivity in science (theory-ladenness)		2	2
6.1. Naive		4	7
6.2. Transitional		1	4
6.3. Informed		2	5

7.6. Appendix F. Data Analysis (Part 1)

<p>Prelab</p>	<p>Personal goals</p> <p><Internals\\Interview Data\\Interview 1> - § 1 reference coded [0.21% Coverage]</p> <p>Reference 1 - 0.21% Coverage I tried to get as much done as possible</p> <p><Internals\\Interview Data\\Interview 2> - § 3 references coded [0.54% Coverage]</p> <p>Reference 1 - 0.16% Coverage the aim was to determine the relaxation time of caffeine</p> <p>Reference 2 - 0.14% Coverage to learn how to use the benched up NMR machine</p> <p>Reference 3 - 0.24% Coverage we also used NMR to determine the peaky A (?), isoelectric point of the amino acid</p> <p><Internals\\Interview Data\\Interview 3> - § 3 references coded [0.39% Coverage]</p> <p>Reference 1 - 0.16% Coverage part 1 was a kinetic study. So, first order, swayer rate coefficient</p> <p>Reference 2 - 0.10% Coverage determining second order rate coefficient</p> <p>Reference 3 - 0.12% Coverage using the UV 1800 spectrometer to measure absorbance</p> <p><Internals\\Interview Data\\Interview 4> - § 2 references coded [0.31% Coverage]</p> <p>Reference 1 - 0.09% Coverage to finish part 2</p> <p>Reference 2 - 0.22% Coverage I wanted to make sense of what I've done</p> <p><Internals\\Interview Data\\Interview 5> - § 3 references coded [0.91% Coverage]</p> <p>Reference 1 - 0.23% Coverage analyse cigarette smoke using an infrared spectrometer</p> <p>Reference 2 - 0.58% Coverage the first part was pretty much finding the information, getting the spectra. And the second part there was a lot more data processing</p> <p>Reference 3 - 0.10% Coverage hoping to finish part 2</p> <p><Internals\\Interview Data\\Interview 6> - § 1 reference coded [0.92% Coverage]</p> <p>Reference 1 - 0.92% Coverage I didn't really have a big goal or anything. Just sort of... it was a bit easier than the previous NMR one, cause that one was quite difficult</p>	
	<p>Preparing for lab</p> <p><Internals\\Interview Data\\Interview 1> - § 5 references coded [2.66% Coverage]</p>	<p>Better preparation</p> <p><Internals\\Interview Data\\Interview 1> - § 3 references coded [1.57% Coverage]</p>

	<p>Reference 1 - 0.56% Coverage I had some reading online that I tried to do but didn't have access, some of the files with some problem.</p> <p>Reference 2 - 0.16% Coverage I read through the lab manual.</p> <p>Reference 3 - 0.82% Coverage There was a video about using spottance (?) we used last year, but for this experiment we did the week before. That was the prelab video that I watched.</p> <p>Reference 4 - 0.53% Coverage No quiz? 1: No, so you don't really have to do this? The week before we had some proper questions.</p> <p>Reference 5 - 0.60% Coverage There was like 10 questions or something. And answering these will improve our understanding of the experiment.</p> <p><Internals\\Interview Data\\Interview 2> - § 3 references coded [0.70% Coverage]</p> <p>Reference 1 - 0.33% Coverage trainings to use the instrument before the experiment? 2: There was a prelab that was showing us how to do it.</p> <p>Reference 2 - 0.08% Coverage I watched the prelab video.</p> <p>Reference 3 - 0.29% Coverage online discussion forum? 2: I haven't used it yet this year but I used it a few times last year.</p> <p><Internals\\Interview Data\\Interview 4> - § 6 references coded [3.00% Coverage]</p> <p>Reference 1 - 0.28% Coverage If they give a paper, I print it, I go through it.</p> <p>Reference 2 - 0.29% Coverage I try to see if I understand what they're explaining.</p> <p>Reference 3 - 0.34% Coverage compare the data that I got with the data that this paper has.</p> <p>Reference 4 - 0.27% Coverage When I don't know some stuff, I try to Google it.</p> <p>Reference 5 - 0.63% Coverage I didn't use it. Coz, for part 1 they're ok coz the eManual tells you a bit about the procedure. So that's easier.</p> <p>Reference 6 - 1.18% Coverage I read through the paper on the link they gave us, and I could understand more or less what you had to look for, the energy of the orbitals, but I didn't really understand why I got that number and not the other.</p> <p><Internals\\Interview Data\\Interview 5> - § 7 references coded [2.32% Coverage]</p> <p>Reference 1 - 0.10% Coverage I didn't really prepare.</p> <p>Reference 2 - 0.09% Coverage I prepared last week.</p> <p>Reference 3 - 0.18% Coverage I read the materials they provided for us.</p>	<p>Reference 1 - 0.38% Coverage Probably some more reading so that we knew what we were trying to find.</p> <p>Reference 2 - 0.46% Coverage We just came up with some kind of graph but we were like... do you know what that mean?</p> <p>Reference 3 - 0.74% Coverage H: So, interpreting the data and making sense of what you get? 1: Yeah. And like... knowing what to expect as well, would have been useful.</p> <p><Internals\\Interview Data\\Interview 2> - § 1 reference coded [0.30% Coverage]</p> <p>Reference 1 - 0.30% Coverage There's some issues that you don't realise might come up until you actually do the lab and you go back</p> <p><Internals\\Interview Data\\Interview 3> - § 1 reference coded [0.40% Coverage]</p> <p>Reference 1 - 0.40% Coverage would definitely have been to try and attempt part 2 before the lab, so when we go in we could ask questions rather than sitting on the bench in the lab and do bookwork.</p> <p><Internals\\Interview Data\\Interview 4> - § 3 3 references coded [1.98% Coverage]</p> <p>Reference 1 - 0.82% Coverage I think it will improve the lab experience here if there is some discussion before the lab starts, not only on methodology but also a bit of theory</p> <p>Reference 2 - 0.67% Coverage if I can find more papers to help me understand better, that will help a lot. You know, to have different point of view.</p> <p>Reference 3 - 0.49% Coverage If I have to change something, I would look for more articles and try to understand them.</p> <p><Internals\\Interview Data\\Interview 6> - § 2 2 references coded [2.51% Coverage]</p> <p>Reference 1 - 1.84% Coverage Well, maybe spend a bit more time. I mean, I spent quite a lot of time for the NMR but I think it wasn't very efficient, cause I didn't really know where I could find the information to fill these gaps. A lot of time, I spent time reading the material that wasn't really relevant.</p> <p>Reference 2 - 0.68% Coverage For the computer simulation I didn't really prepare that much because I had to focus on the lab report.</p>
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	<p>Reference 4 - 0.30% Coverage I thought the preparation last week would be sufficient but it wasn't.</p> <p>Reference 5 - 0.29% Coverage I should have read the scientific paper that they provided for us.</p> <p>Reference 6 - 0.42% Coverage For the first experiment, I read through the manual and I watched the videos that were provided.</p> <p>Reference 7 - 0.93% Coverage Probably... I only need like half an hour (?) to prepare for a lab. So it's not a huge problem. It's more of a problem when it's 10 o'clock at night and I need to go to bed rather than spending half an hour on prelab.</p> <p><Internals\\Interview Data\\Interview 6> - § 7 references coded [3.91% Coverage]</p> <p>Reference 1 - 1.03% Coverage We didn't have to come up with much of the procedure for the second part ourselves because the linked article basically told you everything you needed to do.</p> <p>Reference 2 - 0.49% Coverage We were also a bit rustic. We hadn't done lab since like the whole summer.</p> <p>Reference 3 - 0.12% Coverage I read the articles</p> <p>Reference 4 - 0.62% Coverage I tried to figure out the settings and stuff, cause we haven't really covered relaxation times</p> <p>Reference 5 - 0.46% Coverage I did quite a bit reading on that, just to understand how that worked.</p> <p>Reference 6 - 0.46% Coverage Any question about procedure, I asked the demonstrator and instructor.</p> <p>Reference 7 - 0.73% Coverage H: What about the pre-lab videos? 6: Yeah, I went through all of that and the link found in the article as well.</p>	
	<p>Prelab work</p> <p><Internals\\Interview Data\\Interview 1> - § 4 references coded [1.82% Coverage]</p> <p>Reference 1 - 0.39% Coverage most effective in promoting your learning? 1: Probably the online forum.</p> <p>Reference 2 - 0.65% Coverage Especially while writing the lab report, they're just really quick at replying. And easy when people have the same issues.</p> <p>Reference 3 - 0.26% Coverage It's more useful when we have the same struggles.</p> <p>Reference 4 - 0.52% Coverage Dr S is there. He answers us but if somebody else knows the right answer, they can do it too.</p> <p><Internals\\Interview Data\\Interview 2> - § 10 references coded [5.42% Coverage]</p> <p>Reference 1 - 0.11% Coverage</p>	<p>Most effective prelab</p> <p><Internals\\Interview Data\\Interview 1> - § 4 references coded [1.82% Coverage]</p> <p>Reference 1 - 0.39% Coverage most effective in promoting your learning? 1: Probably the online forum.</p> <p><Internals\\Interview Data\\Interview 2> - § 1 reference coded [1.13% Coverage]</p> <p>Reference 1 - 1.13% Coverage the videos are definitely helpful because, for example when you have to use a new instrument it's hard to imagine what's going on when there's a lot of steps you have to follow that's written in the manual, but when there's a video showing you, oh you press that, you insert it into there, it's much easier and it gets less time to get used to the machine when you're in the lab.</p> <p><Internals\\Interview Data\\Interview 3> - § 7 references coded [2.70% Coverage]</p> <p>Reference 1 - 0.12% Coverage</p>

	<p>the theory session was in the manual.</p> <p>Reference 2 - 0.35% Coverage It's also very helpful because other people may have the same question. They asked it for you and you don't have to.</p> <p>Reference 3 - 0.63% Coverage the forum? 2: I think that's a good idea. Definitely helpful because usually the questions people have, a lot of people have them and it's easier than having to chase the demonstrator around or email Dr Seery.</p> <p>Reference 4 - 1.15% Coverage I think the videos are definitely helpful because, for example when you have to use a new instrument it's hard to imagine what's going on when there's a lot of steps you have to follow that's written in the manual, but when there's a video showing you, oh you press that, you insert it into there, it's much easier and it gets less time to get used to the machine when you're in the lab.</p> <p>Reference 5 - 0.14% Coverage the lab manual? 2: It's... ok. It has its flaws</p> <p>Reference 6 - 0.36% Coverage For example, for this experiment, the procedure for part 1 is not in the manual. We had to print it out. So it was online.</p> <p>Reference 7 - 0.51% Coverage So for some experiments there are links in both printed and electronic versions, but for the NMR experiment, the procedure for part 1 was only on the electronic lab manual.</p> <p>Reference 8 - 0.35% Coverage I think the lab manual is a bit confusing, especially when it came to how to use the SIM card, the programme we used.</p> <p>Reference 9 - 0.77% Coverage We hadn't used anything like that before. We didn't really know what PCA was. And that experiment didn't even have the prelab video, so it was quite difficult to ... So, the PCA experiment was quite difficult. It took sometimes to figure out what was going on.</p> <p>Reference 10 - 1.05% Coverage H: So, without the prelab video, do you think you were prepared enough for that experiment? 2: I don't think so. Not necessarily a video but some sort of explanation on what PCA was, it might have been helpful. We had a few suggested articles, but the articles... they were like actual journal articles that aimed at people who understand what PCA is.</p> <p><Internals\\Interview Data\\Interview 3> - § 8 references coded [2.52% Coverage]</p> <p>Reference 1 - 0.11% Coverage background theory? 3: Yeah, in the lab manual.</p> <p>Reference 2 - 0.14% Coverage They're a lot more helpful and organic and inorganic labs.</p> <p>Reference 3 - 0.10% Coverage it goes over what you're gonna be doing.</p> <p>Reference 4 - 0.05% Coverage</p>	<p>it gives most useful video, the postlab analysis.</p> <p>Reference 2 - 0.19% Coverage It's a brief video on how to present your data, what would the best method be.</p> <p>Reference 3 - 0.23% Coverage It guides you in the right direction, so you don't waste your time working out what you need to do</p> <p>Reference 4 - 0.27% Coverage I think the discussion board is best by far, because it provides a sort of channel between yourself and Dr Seery</p> <p>Reference 5 - 0.06% Coverage that's easily accessible</p> <p>Reference 6 - 0.42% Coverage I don't know anyone who's ever gone to see the professor, for the organic and inorganic. But if there were discussion boards, it would be easier and more accessible to do that.</p> <p>Reference 7 - 1.42% Coverage Sometimes when you sit down and do your lab report, and you get stumped to the first hurdle, something that's relatively trivial, once you've been told it. You have no idea where to start, you do all the origin graphs in Excel, it doesn't come out right, because you forgot one thing, or you didn't have to something. And you can wait for hours, whole day, mornings, doesn't work. Whereas if I could just go to discussion board, ask the questions, come back to it once it's been answered, or lots of time other people would ask the same question, you can just refer back. It saves so much time.</p> <p><Internals\\Interview Data\\Interview 4> - § 2 references coded [2.45% Coverage]</p> <p>Reference 1 - 0.54% Coverage Last year we had to do a quiz at home. I liked it too but I think the discussion is more helpful.</p> <p>Reference 2 - 1.91% Coverage H: Do you think it's not covered by the online discussion forum? 4: I don't think it will be the same. I think face-to-face discussion is better. Maybe it's personal but I feel sometimes I understand what's going on but if someone asks me, I realise maybe I don't understand it that well. I think 10 minutes face-to-face will be more helpful.</p> <p><Internals\\Interview Data\\Interview 5> - § 2 references coded [1.71% Coverage]</p> <p>Reference 1 - 0.56% Coverage I really like the videos. I think they make me feel more confident, knowing and understanding what techniques are expected of me.</p> <p>Reference 2 - 1.15% Coverage When it's reading, I never know if it's going to be preferable to read the manual or the reading that's provided as well. I know that I should do both, but I'm usually short of time when I got other stuff to learn, lab reports to write, and presentations to write.</p> <p><Internals\\Interview Data\\Interview 6> - § 1 reference coded [2.83% Coverage]</p>
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	<p>You know in advance.</p> <p>Reference 5 - 0.06% Coverage It shows you how to do it.</p> <p>Reference 6 - 0.10% Coverage Sometimes it's hard to know where to start.</p> <p>Reference 7 - 1.59% Coverage H: Can you describe more how it goes in the other labs? 3: So in the second year, inorganic was the worse. There was no videos at all. Sometimes there was 10 questions, you just look up the answer on the internet. And then once discussed you type in another tab and you know, it doesn't seem very applicable. But the organic has some videos, experimental techniques from Dr Kirsopp, but they were few and far between. How to use the machines, rather than how to do the experiment. So instead of like saying on this experiment you're mixing this, this is how to operate as you use, it would just be this is how to submit an NMR sample, this is how to use the IR.</p> <p>Reference 8 - 0.37% Coverage Discussion forum is very useful. It started last year in second year and it was full. Everyone was asking lots of questions, you could find out information.</p> <p><Internals\\Interview Data\\Interview 4> - § 1 reference coded [0.23% Coverage]</p> <p>Reference 1 - 0.23% Coverage Here you know what you are expected to do.</p> <p><Internals\\Interview Data\\Interview 5> - § 1 reference coded [1.94% Coverage]</p> <p>Reference 1 - 1.94% Coverage H: Are you aware of the online discussion forum? Have you ever used that? 5: Yes. I have used that in the past. I haven't this year. I emailed Dr S when I had an issue last year, he was very good and attentive. And one of my friends had put a question form last year and he was very good. Cause it was a similar question, but she already asked it, and she told me about it. So, he's very good at keeping that up to date and checking it.</p> <p><Internals\\Interview Data\\Interview 6> - § 1 reference coded [0.74% Coverage]</p> <p>Reference 1 - 0.74% Coverage this one was bit smoother, which it was, cause obviously the supplementary material's really laid out very easily</p>	<p>Reference 1 - 2.83% Coverage I guess it depends what the aim is, just sort of having the best base for going into the lab, the video does the best job by itself. It's the most accessible, the easiest thing to do, just watching the video, compared to reading articles. That takes more effort. So if there's one thing that could be the video, but you still need some background reading. Especially if it's a concept you haven't done very much in class and stuff.</p>
	<p>Prelab videos</p> <p><Internals\\Interview Data\\Interview 1> - § 4 references coded [1.37% Coverage]</p> <p>Reference 1 - 0.34% Coverage It makes you know what you're gonna do before coming to the lab.</p> <p>Reference 2 - 0.46% Coverage Well the videos that I've watched were more how to operate things, like what they mean</p> <p>Reference 3 - 0.27% Coverage they were particularly useful for this experiment.</p> <p>Reference 4 - 0.30% Coverage It doesn't help me learn or anything, just get</p>	<p>Most effective part to promote learning</p> <p><Internals\\Interview Data\\Interview 1> - § 2 references coded [0.70% Coverage]</p> <p>Reference 1 - 0.30% Coverage It doesn't help me learn or anything, just get the data</p> <p>Reference 2 - 0.40% Coverage There might be for other experiments but the one that I had didn't have it.</p> <p><Internals\\Interview Data\\Interview 2> - § 2 references coded [0.83% Coverage]</p> <p>Reference 1 - 0.31% Coverage In some of the videos they explain the theory behind it, which is easier than reading</p>

	<p>the data.</p> <p><Internals\\Interview Data\\Interview 2> - § 5 references coded [1.04% Coverage]</p> <p>Reference 1 - 0.23% Coverage For that experiment there was just that video on how to use the NMR machine.</p> <p>Reference 2 - 0.21% Coverage They're usually under 10 minutes, which doesn't take up much of my time.</p> <p>Reference 3 - 0.28% Coverage it makes it easier to know what you're doing in the lab because you've already seen the stuff.</p> <p>Reference 4 - 0.16% Coverage It's more engaging than the text on a piece of paper.</p> <p>Reference 5 - 0.16% Coverage Usually an experiment with the video goes much faster.</p> <p><Internals\\Interview Data\\Interview 3> - § 13 references coded [2.33% Coverage]</p> <p>Reference 1 - 0.06% Coverage I found this very useful.</p> <p>Reference 2 - 0.72% Coverage There were 3 videos on the electronic lab manual. The first one was the techniques used. So Dr Seery went over the UV/vis spec, how to do the cuvettes, etc. and then 1 was on the analysis. What you have to be doing. And the other one was on post data analysis, what you have to be doing in your report.</p> <p>Reference 3 - 0.20% Coverage In the video, Dr Seery went over the rate equations, rate laws... for the experiment.</p> <p>Reference 4 - 0.11% Coverage when writing up my report, I used the video.</p> <p>Reference 5 - 0.06% Coverage You don't forget anything.</p> <p>Reference 6 - 0.10% Coverage You know what you have to do afterwards.</p> <p>Reference 7 - 0.11% Coverage It often starts from real beginner's knowledge.</p> <p>Reference 8 - 0.26% Coverage Sometimes we haven't done a technique for a year and a half. This year, I just go and straight deep into it.</p> <p>Reference 9 - 0.16% Coverage I understand he always builds up from the start, like basic theory.</p> <p>Reference 10 - 0.07% Coverage Doesn't start too difficult.</p> <p>Reference 11 - 0.09% Coverage refresh your memory, which is important</p> <p>Reference 12 - 0.08% Coverage it's specific for each experiment</p> <p>Reference 13 - 0.31% Coverage H: In terms of the amount of information, what do you think? 3: They're often shorts between 3 and 9 minutes. So good amount.</p>	<p>through the manual.</p> <p>Reference 2 - 0.51% Coverage H: So you haven't done anything with that instrument before in the previous years? 2: No. It's brand new and watching the video is like... Ah, you press that, you press that.</p> <p><Internals\\Interview Data\\Interview 3> - § 1 reference coded [0.26% Coverage]</p> <p>Reference 1 - 0.26% Coverage The video tells you what you're gonna be doing in postlab analysis, make sure you write down the right data.</p> <p><Internals\\Interview Data\\Interview 4> - § 1 reference coded [0.63% Coverage]</p> <p>Reference 1 - 0.63% Coverage I really like that we had to read through the chemistry educational paper. In Spain they didn't give us the link.</p> <p><Internals\\Interview Data\\Interview 5> - § 2 references coded [1.06% Coverage]</p> <p>Reference 1 - 0.57% Coverage there was one on kind of... data processing, how to do the calculations, which was very helpful, because there was a guide to the data</p> <p>Reference 2 - 0.48% Coverage putting it to context with the video, made a big difference to our result, I think. Helped us to understand it.</p>
	<p>Suggestions for modification</p> <p><Internals\\Interview Data\\Interview 1> - § 3 references coded [1.33% Coverage]</p> <p>Reference 1 - 0.58% Coverage some more resources just so it's easier to know more of the background of what you're doing before you do it</p> <p>Reference 2 - 0.44% Coverage For example on relaxation times, I'd like some more background reading about that.</p> <p>Reference 3 - 0.31% Coverage A recommendation on further reading, something like that.</p> <p><Internals\\Interview Data\\Interview 2> - § 3 references coded [0.83% Coverage]</p> <p>Reference 1 - 0.13% Coverage It would be useful to have a video for PCA.</p> <p>Reference 2 - 0.25% Coverage H: For every experiment? 2: Yeah. Maybe if it's something like... unknown techniques.</p> <p>Reference 3 - 0.45% Coverage we were surprised that we didn't know what PCA was and that we hadn't done that before. If the video had been done, maybe this wouldn't have happened.</p> <p><Internals\\Interview Data\\Interview 3> - § 2 references coded [0.44% Coverage]</p> <p>Reference 1 - 0.30% Coverage This might be trivial, for me a lot are fine but</p>	

	<p><Internals\\Interview Data\\Interview 4> - § 3 references coded [1.53% Coverage]</p> <p>Reference 1 - 0.93% Coverage That was really helpful but I have to say I had some trouble understanding the video just because of English. Maybe it's just the accent. So I had to make more effort.</p> <p>Reference 2 - 0.34% Coverage I think the good thing is it makes you familiar with the lab.</p> <p>Reference 3 - 0.27% Coverage I agree that the videos are visual, so it helps.</p> <p><Internals\\Interview Data\\Interview 5> - § 2 references coded [1.92% Coverage]</p> <p>Reference 1 - 0.84% Coverage Dr S, he said on the video that the point of the lab isn't to teach you theory. It's to improve your skills at writing lab report essentially, using the equipment and things like that.</p> <p>Reference 2 - 1.08% Coverage In terms of time, that the course takes up, I find that I often don't have the time to do the reading. I often prefer the videos because it's something different. It feels like I'm using my brain differently. It's a nice break, if that makes sense.</p> <p><Internals\\Interview Data\\Interview 6> - § 4 references coded [4.38% Coverage]</p> <p>Reference 1 - 1.21% Coverage The video was really good. It's useful to see... how you... cause there is something different in seeing how to put it down in the machine, where you find the settings and click everything.</p> <p>Reference 2 - 1.13% Coverage H: In the pre-lab video, is there any background theory discussed? 6: I think it's just the main point what you're looking for in the result. I think it is briefly outlined.</p> <p>Reference 3 - 0.86% Coverage H: So, there's not much about theory? 6: Not that I can recall. They're not too in depth. I mean you can't do 30 mins video either.</p> <p>Reference 4 - 1.17% Coverage It puts all the right things in context. You see the actual lab. You see the equipment, which button to press, by which you can visualise what you'll actually be doing in the lab.</p>	<p>for international students, understanding Dr Seery could be quite difficult.</p> <p>Reference 2 - 0.14% Coverage Subtitle would be helpful. Or in the comments. A manuscript.</p> <p><Internals\\Interview Data\\Interview 4> - § 4 references coded [1.55% Coverage]</p> <p>Reference 1 - 0.44% Coverage H: Would you prefer subtitles in the video? 4: Yeah. That would be very helpful.</p> <p>Reference 2 - 0.18% Coverage Subtitles would be very helpful.</p> <p>Reference 3 - 0.32% Coverage Maybe there could be more videos on the analysis of data.</p> <p>Reference 4 - 0.62% Coverage the videos are more visual than text. It could be useful to not only give a hint but maybe go deeper than that.</p> <p><Internals\\Interview Data\\Interview 6> - § 2 references coded [1.73% Coverage]</p> <p>Reference 1 - 0.62% Coverage Maybe you could a bit more background theory. Nothing too in depth but more converged on that.</p> <p>Reference 2 - 1.12% Coverage Maybe divide the video into two sections, like what you're doing in the lab and more like... the theory behind it. Especially for the stuff you haven't really done in class.</p> <p>Prelab videos and NoS</p> <p><Internals\\Interview Data\\Interview 1> - § 1 reference coded [0.26% Coverage]</p> <p>Reference 1 - 0.26% Coverage I don't think I can tell you anything about that.</p> <p><Internals\\Interview Data\\Interview 2> - § 6 references coded [1.49% Coverage]</p> <p>Reference 1 - 0.15% Coverage Explain the general science behind the experiment.</p> <p>Reference 2 - 0.41% Coverage If I'm watching the video that... a prelab video to help me prepare for the lab, I don't want an extra 5 minutes on who won the Nobel prize.</p> <p>Reference 3 - 0.23% Coverage It gives you a good background of science, but not background of... background.</p> <p>Reference 4 - 0.31% Coverage I think what would be interesting is not... the history of it but maybe potential application or something.</p> <p>Reference 5 - 0.11% Coverage Some sort of real-world application.</p> <p>Reference 6 - 0.28% Coverage So it's interesting because it shows that you're not doing some sort of pointless experiment.</p>
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NoS	<p>View on NoS</p> <p><Internals\\Interview Data\\Interview 1> - § 1 reference coded [0.80% Coverage]</p> <p>Reference 1 - 0.80% Coverage I would agree with the second. I mean, I don't doubt that it will change as we find out more things. But I'm not unhappy with what we have currently.</p> <p><Internals\\Interview Data\\Interview 2> - § 4 references coded [1.18% Coverage]</p> <p>Reference 1 - 0.79% Coverage I think it's true how a lot of it is just a model that helps explain what's going on, because for example, molecular orbital theory, it's a big theory that explains a lot of stuff but it's more a mathematical approach to explaining something, as far as I understand.</p> <p>Reference 2 - 0.07% Coverage it's good while it works.</p> <p>Reference 3 - 0.23% Coverage I think that's the interesting thing about science, how it's always changing.</p> <p>Reference 4 - 0.09% Coverage science is a bit philosophical.</p> <p><Internals\\Interview Data\\Interview 3> - § 1 reference coded [0.96% Coverage]</p> <p>Reference 1 - 0.96% Coverage</p>	<p>Argument</p> <p><Internals\\Interview Data\\Interview 1> - § 2 references coded [0.99% Coverage]</p> <p>Reference 1 - 0.77% Coverage I think knowledge will keep developing. I mean they've not even told us everything, coz like... everything you thought was wrong, could be right.</p> <p>Reference 2 - 0.23% Coverage I reckon there's still more we don't know.</p> <p><Internals\\Interview Data\\Interview 2> - § 1 reference coded [0.79% Coverage]</p> <p>Reference 1 - 0.79% Coverage People thought the atom... the plump pudding model was how they thought it was, a mass of positive charge and and negatively charged electrons and it expands and it completely changed, just like the whole atomic structure. It's been developed over the past centuries.</p> <p><Internals\\Interview Data\\Interview 3> - § 1 reference coded [0.39% Coverage]</p> <p>Reference 1 - 0.39% Coverage As a scientist, like you said, in training, I expect to use the knowledge I have, not to have to overly question the whole paradigm, the whole problem behind it.</p> <p><Internals\\Interview Data\\Interview 4> - §</p>

	<p>I think that's very accurate. We can only use the knowledge we've got, then I guess we build up our repertoire using that knowledge. And then if something comes along, there is a change, sort of revolutionary. If they find something we didn't already know, quantum mechanical, answers to thing that previously haven't been answered, and then it would have to start again, build up our knowledge on that.</p> <p><Internals\\Interview Data\\Interview 5> - § 4 references coded [1.12% Coverage] Reference 1 - 0.18% Coverage the point of science is to find the truth.</p> <p>Reference 2 - 0.47% Coverage I do understand both points of view, because I suppose it's two different ways of looking at the same thing</p> <p>Reference 3 - 0.18% Coverage You can't just have a belief, in science.</p> <p>Reference 4 - 0.30% Coverage I guess that's just an aspect of science, that science is stressful.</p> <p><Internals\\Interview Data\\Interview 6> - § 1 reference coded [1.51% Coverage]</p> <p>Reference 1 - 1.51% Coverage I'm leaning more towards the second one. I find it difficult to be able to probably believe that you can know something definitively. There's so much we don't understand in the world that to say something is absolutely this way is</p>	<p>2 references coded [2.82% Coverage]</p> <p>Reference 1 - 1.27% Coverage When you were a child, they explained that science is a universal truth. The other courses and literature in high school, that's not science because it's subjective opinion. Then you got here. I don't think we know the truth yet.</p> <p>Reference 2 - 1.55% Coverage I think science tries to explain why things happen, but we don't know yet the whole truth. Coz there are many theories and many hypotheses, and if that falls down then everything falls down. I don't believe that science is the absolute truth. Science makes sense. It's not magic.</p> <p><Internals\\Interview Data\\Interview 5> - § 5 references coded [1.70% Coverage]</p> <p>Reference 1 - 0.49% Coverage those scientist that don't believe it's true, I can understand their viewpoint, because they want to see evidence</p> <p>Reference 2 - 0.33% Coverage I've no doubt because they're scientists, and science is collecting evidence</p> <p>Reference 3 - 0.31% Coverage If there was evidence produced, they would then believe that to be true.</p> <p>Reference 4 - 0.26% Coverage as a scientist, you learn more and more about less and less</p> <p>Reference 5 - 0.31% Coverage it's a big part of being a scientist, to be able to apply the knowledge</p> <p>Context of chemistry course</p> <p><Internals\\Interview Data\\Interview 2> - § 1 reference coded [2.51% Coverage]</p> <p>Reference 1 - 2.51% Coverage It's hard to compare the two because it's different but also similar. I think Chemistry 2 was a lot more just developing the techniques and doing different things. Phys chem in first year was not very in depth. Lab was dissolving salts and measuring the temperature. And that was fill in the blank sheets not lab report. And when you get to second year, I think you step up, new type of lab reports. It gets you to think about the actual physical chemistry of the experiment. And third year is kind of build on that. But I think it's quite similar to 2nd year. The only different is that we have to think about our own procedures and stuff like that, but it's not massively different. The experiments are a bit more in depth, because you do 2 experiments over 6 weeks, whereas in 2nd year you did 6 experiments and each of them took a session.</p> <p><Internals\\Interview Data\\Interview 3> - § 9 references coded [5.07% Coverage]</p> <p>Reference 1 - 1.10% Coverage I've done a range of modules, tried everything out, and the only module I really enjoyed, sat down and enjoyed learning it was environmental chemistry, coz it was applicable. I could see how it was useful in society. Every single topic had... it was explained how gases are in the environment,</p>
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		<p>the toxicity of metals in the body. Once we learn difficult theory, it was relevant a thing, you could see it in the world around you. You could discuss it with people.</p> <p>Reference 2 - 0.27% Coverage far too much in this course is just raw chemistry but no application. We never learn about how it's being used.</p> <p>Reference 3 - 0.28% Coverage It was really made quite mundane in some areas, where you literally just robot learning formulas and applying them.</p> <p>Reference 4 - 0.45% Coverage you go to the whole lecture courses in organic chemistry, there must be some really interesting uses, coz the whole point of that chemistry is compounds and we never get to learn about that.</p> <p>Reference 5 - 1.32% Coverage In the first and second year we had optional modules. You could take environmental chemistry. I know someone did medicinal chemistry, but that was as far as it went. I guess we have pharmacology in 3rd year now. It's only Chemistry 3A, Chemistry 3B, split equally between organic, inorganic, physical. In this year there's no option for branching. I know in 4th year, they never used to be, but they start to introduce it, more optional modules. So next year we hopefully have the choice. I really hope we do. If it's not, it's only raw chemistry again.</p> <p>Reference 6 - 0.33% Coverage That would be interesting. Well, geochemistry, you know, geology and the chemistry behind that... but no... we had to do really mundane stuff.</p> <p>Reference 7 - 0.56% Coverage They never really used to it. So it was only one optional, but they change and reprogramme and I signed up to it. I said definitely. Where there's an option to do much more optional module in 4th year, I think they start to change it.</p> <p>Reference 8 - 0.38% Coverage But having a whole 3rd year where you're in 9 to 5 each day and you don't learn like any application, doesn't instil any enthusiasm or interest in the course.</p> <p>Reference 9 - 0.38% Coverage there should definitely be modules in all years where you can explore an area of chemistry that is not just solitary environment, like sustainable geochemistry.</p>
	<p>Instructional features influencing view on NoS</p> <p><Internals\\Interview Data\\Interview 1> - § 2 references coded [2.36% Coverage]</p> <p>Reference 1 - 1.81% Coverage So the postlab, the report, there's a lot of independent study that we had to do quite long and you have to understand what's going on. So that's a good place to start investigating. You have to find out sources and not always stuff you've been told in lectures. So you have to go out of your way, to be able to back up what you've found.</p> <p>Reference 2 - 0.55% Coverage Having some understanding about what</p>	

	<p>you're gonna do. Makes you think about like... why you're doing it.</p> <p><Internals\\Interview Data\\Interview 2> - § 1 reference coded [1.37% Coverage]</p> <p>Reference 1 - 1.37% Coverage I think report writing is interesting because in phys chem a lot of it you have to do your own reading. It's not like in organic chemistry experiment where you like do that, add that to that, this is the NMR spectrum. This is what happened. For phys chem you have to look into it, understand it, and a lot of it just find it quite interesting and motivational. It gives you thinking about what's happening, what you're doing makes sense. It comes from your lab.</p> <p><Internals\\Interview Data\\Interview 3> - § 1 reference coded [0.28% Coverage]</p> <p>Reference 1 - 0.28% Coverage I never had any thought beyond the experiment. It could've been a passing comment but nothing I've really thought of.</p> <p><Internals\\Interview Data\\Interview 4> - § 1 reference coded [1.30% Coverage]</p> <p>Reference 1 - 1.30% Coverage They don't really discuss much in the prelab videos. Normally they're just about instruments. Some talk a little bit about theory, but they never really go deep into it. And I think it would be really nice if they actually got into it.</p> <p><Internals\\Interview Data\\Interview 5> - § 1 reference coded [0.80% Coverage]</p> <p>Reference 1 - 0.80% Coverage You can never know everything. So sometimes when I read the manual, I can get slightly caught up in those details rather than focussing on just accomplishing what I need to accomplish.</p>	
	<p>Prelab work and NoS prior to lab</p> <p><Internals\\Interview Data\\Interview 1> - § 2 references coded [0.77% Coverage]</p> <p>Reference 1 - 0.45% Coverage I think they made a decent stuff for the experiment. We haven't messed anything up.</p> <p>Reference 2 - 0.32% Coverage during the prelab it means you know what you're looking for.</p> <p><Internals\\Interview Data\\Interview 2> - § 1 reference coded [0.59% Coverage]</p> <p>Reference 1 - 0.59% Coverage I think prelab videos just focus purely on the experiment. They don't really focus on the theory. So that's the rough picture of the prelab. There's some theory background but it's not very in depth.</p> <p><Internals\\Interview Data\\Interview 4> - § 1 reference coded [1.28% Coverage]</p> <p>Reference 1 - 1.28% Coverage Yeah, a little bit. The problem is, sometimes I understand everything wrong. I went to the lab, I did everything, but then I got different data, not really what I should have got. Until you've done, you don't really understand it.</p>	

<p>Information management</p> <p><Internals\\Interview Data\\Interview 3> - § 3 references coded [0.65% Coverage]</p> <p>Reference 1 - 0.31% Coverage H: In terms of the amount of information, what do you think? 3: They're often short videos between 3 and 9 minutes. So good amount.</p> <p>Reference 2 - 0.22% Coverage H: So no information overload? 3: Not in the physical lab. It's been quite well organised.</p> <p>Reference 3 - 0.12% Coverage H: Apart from the writeup? 3: Yeah, apart from that.</p> <p><Internals\\Interview Data\\Interview 5> - § 1 reference coded [0.44% Coverage]</p> <p>Reference 1 - 0.44% Coverage I feel I have a lot of time management problem with things like... I wish I have prepared for this lab.</p>	<p>Managing information</p> <p><Internals\\Interview Data\\Interview 2> - § 2 references coded [3.10% Coverage]</p> <p>Reference 1 - 1.25% Coverage Good question. PCA experiment... there was a LOT of new information. You had one lab session to do your experiment and then you have to look at your data and understand what it means. And the demonstrator was like... oh, read a side bit on Symke (?). It explains to you what the parameters on the gap are. And he uses like a lot of statistical jargons, and we were like... what does this mean? Explain it to me in human terms.</p> <p>Reference 2 - 1.85% Coverage Whereas the NMR experiment was... we had the NMR lecture course which definitely helps so we know what relaxation times are, roughly. But prelab material was very helpful. We had 10 or 11 pointers to consider before coming to the lab, so once you read through that, you know what you're doing. It's much easier to handle all the information. I think that's quite the issue with physical lab, how there's gaps of knowledge about the subject. The NMR experiment we had the lecture course, we'd been doing it for a while. PCA, we'd never done it before, no lecture, no video, no anything, which makes it much more difficult.</p> <p><Internals\\Interview Data\\Interview 3> - § 1 reference coded [1.12% Coverage]</p> <p>Reference 1 - 1.12% Coverage Well, they were perfectly reasonable. We get mark for lab notebook, tidiness etc. You get 15 marks overall for keeping your lab notebook, so... like here [showing notebook], and then writing what you're doing as you go along, drawing diagrams. And that encourages you to write things as you go along. Whereas if there's no mark available, I'd be like... fine, yeah... I won't write that, and I'll remember that when I come to it, but it helps because the mark is available.</p> <p><Internals\\Interview Data\\Interview 4> - § 3 references coded [3.15% Coverage]</p> <p>Reference 1 - 1.22% Coverage I didn't think they gave us too much information. It was more like self-understanding. I didn't find they gave us a lot. It was not overwhelming. Even if they could push us a little bit more, it wouldn't be overwhelming.</p> <p>Reference 2 - 0.65% Coverage H: You said you could manage the information, why were you stressed then? 4: Because there was not enough information.</p> <p>Reference 3 - 1.27% Coverage</p> <p>H: Well that's new. 4: They explain what I had to do, but not why I had to do it. For example, when you look at the energy, on the UMO, OMO, bla bla bla. But why do I have to do it? What am I going to explain in the lab report?</p> <p><Internals\\Interview Data\\Interview 5> - § 2 references coded [1.48% Coverage]</p> <p>Reference 1 - 0.93% Coverage I would often ask my lab partner for guidance and I would try and look at it from my point of view, and I try to see if my lab</p>	
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	<p>partner is thinking the same thing. Because sometimes I would doubt that I got it right.</p> <p>Reference 2 - 0.55% Coverage There was something I could just not work out and I had to ask my lab partner, how did you do this. It slows me down sometimes</p>	
	<p>Chemistry behind the experiment</p> <p><Internals\\Interview Data\\Interview 1> - § 1 reference coded [0.55% Coverage]</p> <p>Reference 1 - 0.55% Coverage</p> <p>Like the computer ones, you're not just reading numbers. It'll be very easy to do that absent-mindedly.</p> <p><Internals\\Interview Data\\Interview 2> - § 4 references coded [2.05% Coverage]</p> <p>Reference 1 - 0.45% Coverage when you get to second year, I think you step up, new type of lab reports. It gets you to think about the actual physical chemistry of the experiment.</p> <p>Reference 2 - 0.44% Coverage third year is kind of build on that. But I think it's quite similar to 2nd year. The only different is that we have to think about our own procedures</p> <p>Reference 3 - 0.65% Coverage Honestly I think that the prelab was only showing us how to use the machine, because the first part was to determine the PKA's of the amino acid. I'm not 100% sure but I think the prelab video didn't really mention that</p> <p>Reference 4 - 0.50% Coverage It was only the text in the manual that explains it a bit. It was the stuff from the manual, which was interesting to find out because you could use NMR to find the PKA.</p> <p><Internals\\Interview Data\\Interview 3> - § 1 reference coded [0.77% Coverage]</p> <p>Reference 1 - 0.77% Coverage It's interesting. It's often quite applicable to what we've done in the course. In organic, you literally just do what you've done in the lecture slides. So you can actually look back in those whilst writing your report. In physical, sometimes it's a little bit more difficult but often we use equations we've seen before.</p> <p><Internals\\Interview Data\\Interview 4> - § 1 reference coded [0.52% Coverage]</p> <p>Reference 1 - 0.52% Coverage Sometimes you know the steps you have to do but you don't know why you're doing that exactly.</p> <p><Internals\\Interview Data\\Interview 5> - § 1 reference coded [0.96% Coverage]</p> <p>Reference 1 - 0.96% Coverage I didn't really get the chance to, because there was quite a lot to do in a short amount of time, so I have to focus on competing it at times I didn't get to think about the chemistry in order to be able to complete it.</p>	<p>Relevance of prelab</p> <p><Internals\\Interview Data\\Interview 3> - § 4 references coded [2.33% Coverage]</p> <p>Reference 1 - 0.38% Coverage</p> <p>But having a whole 3rd year where you're in 9 to 5 each day and you don't learn like any application, doesn't instil any enthusiasm or interest in the course.</p> <p>Reference 2 - 0.44% Coverage Apart from the odd one, the computational, we've never done that before. There's a few, I've already done this, kinetic study. But we've done the kinetic one in the lecture beforehand.</p> <p>Reference 3 - 0.89% Coverage Whereas sometimes in inorganic ones, it's chemistry we haven't seen before. So, why would we do that? Give us something we can relate to, something we know about. Otherwise what we're doing is basically a shaft. You're just copying the instruction and doing everything without actually knowing what's going on. So it's good to have done the theory in the lecture before lab.</p> <p>Reference 4 - 0.62% Coverage H: Have you learnt any of that from the prelab? 3: Yeah, definitely. Or even if I haven't learnt it, it refreshed. So kinetics, 2nd year, I think first semester course, so I haven't seen it in about a year. The prelab went over that and refreshed my memory.</p>
	<p>Synchronous lecture and lab</p> <p><Internals\\Interview Data\\Interview 3> - § 2 references coded [1.42% Coverage]</p> <p>Reference 1 - 0.88% Coverage sometimes in inorganic ones, it's chemistry we haven't seen before. So, why would we do that? Give us something we can relate to, something we know about. Otherwise what we're doing is basically a shaft. You're just copying the instruction and doing everything without actually knowing what's going on. So it's good to have done the theory in the lecture before lab.</p> <p>Reference 2 - 0.54% Coverage H: Is the lab synchronous with the lectures? 3: It's often very similar. Not always, but often we would've heard of the experiment or know the mechanisms behind what's going on. We've already done the theory in the lectures.</p>	
	<p>Self-assessing the accomplishment</p> <p><Internals\\Interview Data\\Interview 2> - § 3 references coded [1.06% Coverage]</p>	

	<p>Reference 1 - 0.33% Coverage I definitely learnt a lot of new techniques. Physical chemistry teaches you a lot of instruments, how they work.</p> <p>Reference 2 - 0.25% Coverage Definitely a lot of lab report writing skills, because I like the physical chemistry.</p> <p>Reference 3 - 0.47% Coverage How you need to look stuff up to understand, how to handle and process your data, coz physical lab you do it in pair so you have to work effectively as a team.</p> <p><Internals\\Interview Data\\Interview 3> - § 3 references coded [1.34% Coverage]</p> <p>Reference 1 - 0.38% Coverage there should definitely be modules in all years where you can explore an area of chemistry that is not just solitary environment, like sustainable geochemistry.</p> <p>Reference 2 - 0.43% Coverage So... absorbance, skills of using the UV spectrometer machine. By the end, we had 25 samples so I know exactly how to hold the cuvette, how to put it, how to hold the baseline etc.</p> <p>Reference 3 - 0.53% Coverage the second main learning point is refreshing kinetics, remembering how to find Ray constants and often it can be disheartening when you do all the results and all the discussion but then your results just haven't worked. So</p> <p><Internals\\Interview Data\\Interview 4> - § 1 reference coded [0.52% Coverage]</p> <p>Reference 1 - 0.52% Coverage I think you can understand everything only after you've done everything, not only the prelab.</p> <p><Internals\\Interview Data\\Interview 5> - § 2 references coded [1.70% Coverage]</p> <p>Reference 1 - 0.82% Coverage I need to apply the knowledge, but it's a big part of being a scientist, to be able to apply the knowledge. I think what I get from it is valuable. I learn how to help me think in new ways</p> <p>Reference 2 - 0.89% Coverage This lab session today was quite good because I started off very strongly disliking it and not knowing what I was doing and I did feel like I got some understanding of how to use the programme by the end.</p>	
<p>Affective domain</p> <p><Internals\\Interview Data\\Interview 2> - § 4 references coded [3.68% Coverage]</p> <p>Reference 1 - 0.58% Coverage For phys chem you have to look into it, understand it, and a lot of it just find it quite interesting and motivational. It gives you thinking about what's happening, what you're doing makes sense.</p> <p>Reference 2 - 2.37% Coverage I had to watch a video on YouTube</p>	<p>Feeling during the lab</p> <p><Internals\\Interview Data\\Interview 1> - § 2 references coded [0.46% Coverage]</p> <p>Reference 1 - 0.08% Coverage Honestly fine.</p> <p>Reference 2 - 0.39% Coverage The lab isn't stressful really, but processing the data is a lot harder.</p> <p><Internals\\Interview Data\\Interview 2> - § 4 references coded [1.84% Coverage]</p> <p>Reference 1 - 0.16% Coverage</p>	

<p>explaining PCA. That kinda helped. And then you kind of... ok, now I understand the theory of PCA, but I have my data that I have to analyse and that doesn't really make sense. What I didn't really like about the experiment was... you know what whisky is, where it comes from, what type it is, so... you've got your PCA data and you can vary your parameters, something like that, to get a result that matches your data, but you're not using your results to explain your data which feel like... you know sometimes NMR spectrum is often unknown compound but then you like... cheat a bit... you find a molecular formula that matches it. So you use the molecules to explain your spectrum but not your spectrum to get your molecules. And that's what that experiment felt like.</p> <p>Reference 3 - 0.61% Coverage it's like an unusual opinion, I think. A lot of people seem to dislike it, but I like, for example, if your results don't match the literature, as long as you can explain what went wrong, then it's fine.</p> <p>Reference 4 - 0.12% Coverage i like that there's a research component</p> <p><Internals\\Interview Data\\Interview 3> - § 4 references coded [1.84% Coverage]</p> <p>Reference 1 - 0.35% Coverage H: How have you experienced science so far? 3: At school it was a topic I enjoyed most. I also enjoyed maths, and it went quite nicely with it.</p> <p>Reference 2 - 0.25% Coverage Everyone commented on it, how rude he was. I don't know if he had a hard time. It ruined the atmosphere.</p> <p>Reference 3 - 0.64% Coverage It does make a big difference because upstairs in the organic lab, two ladies are both very funny. They walk around, chat to you, help you. Coz you're in the lab so long, you get to know them. It does massively improve the atmosphere and the friendliness in the lab.</p> <p>Reference 4 - 0.61% Coverage H: So you acknowledge the importance of feeling good in the lab? Keeping the motivation high? 3: Yeah. Definitely. It's 9 to 12 lab and then 2 to 5. We need 2 hours break because if you've been staring at chemicals without it you're being really intense.</p>	<p>Well in my experiment I've been having a lot of fun.</p> <p>Reference 2 - 0.49% Coverage I was in a very good mood, I don't know why. Probably the coffee I had. I knew what was happening, what we were doing, things make sense. Good mood within that all.</p> <p>Reference 3 - 0.79% Coverage H: What a contrast, yeah? 2: Because you came back after 6 months or so, not doing physical lab, and then you were thrown into PCA, none of you have done that or anything, you had to use some sort of new software that no one does than the demonstrators themselves.</p> <p>Reference 4 - 0.40% Coverage You were just not sure what was happening. And you're just there looking at your dots and like... what does this mean? A bit frustrating</p> <p><Internals\\Interview Data\\Interview 3> - § 1 reference coded [0.20% Coverage]</p> <p>Reference 1 - 0.20% Coverage Often quite stressed, coz if you get it wrong, you run out of time, you can't do it.</p> <p><Internals\\Interview Data\\Interview 4> - § 2 references coded [0.60% Coverage]</p> <p>Reference 1 - 0.28% Coverage Sometimes everything is so new and you feel alone.</p> <p>Reference 2 - 0.33% Coverage Sometimes stressed because I didn't know what was going on.</p> <p><Internals\\Interview Data\\Interview 5> - § 3 references coded [3.48% Coverage]</p> <p>Reference 1 - 1.50% Coverage The experiment today... this one was quite frustrating, I would say. I know that sometimes frustration can be a good thing, as it can motivate me to know more. But today at times I felt like I was being hindered by the wording and thing in the lab manual. The way it was explained to me, which doesn't feel like something that should hold me back.</p> <p>Reference 2 - 1.15% Coverage A lot of times I felt confused that what we were doing in the physchem lab so far. And I honestly don't know if that is intentional or not. I'm not sure if they want me to work out for myself, or I should feel more certain. I feel quite doubtful a lot of the time.</p> <p>Reference 3 - 0.83% Coverage I would get stressed. I wouldn't be able to... I suppose enjoy thinking about it, because I knew I had to get the answer, but I guess that's just an aspect of science, that science is stressful.</p> <p><Internals\\Interview Data\\Interview 6> - § 1 reference coded [0.62% Coverage]</p> <p>Reference 1 - 0.62% Coverage we got some data we could use and we couldn't do anything about that. It was frustrating a bit.</p> <p>Confidence</p> <p><Internals\\Interview Data\\Interview 1> - § 1 reference coded [0.43% Coverage]</p>	
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	<p>Reference 1 - 0.43% Coverage 6? Yeah. I wouldn't like... go into the lab and not being as prepared as possible.</p> <p><Internals\\Interview Data\\Interview 2> - § 2 references coded [0.67% Coverage]</p> <p>Reference 1 - 0.17% Coverage Depends on the experiment. The NMR was like a solid 8.5.</p> <p>Reference 2 - 0.50% Coverage The PCA... started off at 2. The first part where you measure the UV/vis spectra, that was like a 9, but when it came to PCA analysis. You're kind of descending over time</p> <p><Internals\\Interview Data\\Interview 3> - § 4 references coded [1.14% Coverage]</p> <p>Reference 1 - 0.04% Coverage I'd say... about 6.</p> <p>Reference 2 - 0.39% Coverage Often before I do something I check with my partner and check with the demonstrator, because doing something and getting it wrong is a lot worse than asking someone.</p> <p>Reference 3 - 0.47% Coverage And if you make a mistake, some of the experiments takes 2 hours to run etc. If you do something wrong in the first stage, that's kind of ruin the whole lab. So I often do double check everything.</p> <p>Reference 4 - 0.23% Coverage So those are the learning point, experimental, confidence, and now back myself using the machine.</p> <p><Internals\\Interview Data\\Interview 4> - § 1 reference coded [0.07% Coverage]</p> <p>Reference 1 - 0.07% Coverage I'd say 6.5.</p> <p><Internals\\Interview Data\\Interview 5> - § 3 references coded [1.35% Coverage]</p> <p>Reference 1 - 0.56% Coverage I really like the videos. I think they make me feel more confident, knowing and understanding what techniques are expected of me.</p> <p>Reference 2 - 0.33% Coverage Today I would say... maybe 5. I felt completely out of my depth, not at ease.</p> <p>Reference 3 - 0.47% Coverage The first one maybe a 7? Partly because we've done physical lab before with that, which was really helpful.</p>	
<p>Challenges in the lab</p> <p><Internals\\Interview Data\\Interview 1> - § 1 reference coded [0.38% Coverage]</p> <p>Reference 1 - 0.38% Coverage Sometimes it's tricky because of the lab report and stuff can be hefty.</p> <p><Internals\\Interview Data\\Interview 2> - § 1 reference coded [1.46% Coverage]</p> <p>Reference 1 - 1.46% Coverage Because you came back after 6 months or so, not doing physical lab, and then you were thrown into PCA, none of you have done that or anything, you had to use some sort of new software that no one does than the demonstrators themselves. You were just not sure what was happening. And you're just there looking at your dots and like... what does this mean? A bit frustrating. I think. We finally got the grasp of PCA at he the end of the</p>		

<p>last session. So, we managed to write a lab report but...</p> <p><Internals\\Interview Data\\Interview 3> - § 2 references coded [2.26% Coverage]</p> <p>Reference 1 - 0.14% Coverage I find the technician quite rude and in some way aggressive.</p> <p>Reference 2 - 2.12% Coverage It was 20 to 5 and we spent 6 hours of the day doing UV/vis spectrometry. All my results on Excel on computer. All on UV probe software. The lab had 20 minutes left, so I had plenty of time. And he came over and he said I'm turning off this computer, it's 20 to, we need to tidy up, save everything. I was in another room doing some washing up. So I had to run over, he was standing there. I had to save all my data, shutting it down, and then he was going over, barking order telling people what to do. It was just like ruined the whole atmosphere in the lab. Every 20 minutes he would come out, run off the lab, and just point out really insignificant things. So, we had to label our bottles. So I labelled it, 1% STS solution on a piece of paper next to it. He came out and said you can't write STS. You have to write the full name. He made me do it again on every single glassware.</p> <p><Internals\\Interview Data\\Interview 5> - § 1 reference coded [1.03% Coverage]</p> <p>Reference 1 - 1.03% Coverage I wish I have prepared for this lab. I just felt I couldn't because I needed to do things like tutorial questions, and the rest of the course. The lab report, and this oral presentation that we have to do on Monday. I need to write that.</p> <p><Internals\\Interview Data\\Interview 6> - § 2 references coded [1.97% Coverage]</p> <p>Reference 1 - 1.53% Coverage First half of that session was fine but in the afternoon the machine kept freezing so we couldn't really finish everything in the experiment. But Dr Bell had a look at it and found out that something in the machine wasn't stabilised.</p> <p>Reference 2 - 0.44% Coverage We spent 2.5 hours trying to run the same scan over and over again.</p>	
<p>Role of demonstrator</p> <p><Internals\\Interview Data\\Interview 1> - § 1 reference coded [1.05% Coverage]</p> <p>Reference 1 - 1.05% Coverage Maybe the biggest issue would be, sometimes the demonstrator... the one we had hadn't demonstrated the experiment, so we didn't know how to use the machine properly. I think that was the main issue.</p> <p><Internals\\Interview Data\\Interview 2> - § 2 references coded [1.64% Coverage]</p> <p>Reference 1 - 0.66% Coverage I haven't really talked about the fact that... I mentioned that to the demonstrators. One of them thought that the PhD student who wrote the experiment was supposed to prepare some sort of information... a prelab video on PCA.</p> <p>Reference 2 - 0.98% Coverage Depending on your group, my demonstrator was not quite helpful but our lab supervisor, the person who lectured the ionised solution, he helped us roughly. But I've heard other groups complaining about they didn't know what was going on, the demonstrator didn't really help. They found it very frustrating when you get into much.</p> <p><Internals\\Interview Data\\Interview 3> - § 1 reference coded [0.30% Coverage]</p> <p>Reference 1 - 0.30% Coverage often demonstrators are very helpful. They're normally quite friendly. You speak to them, chat to them whilst you're waiting.</p> <p><Internals\\Interview Data\\Interview 4> - § 2 references coded [3.36% Coverage]</p> <p>Reference 1 - 1.55% Coverage It would be great if the demonstrator asks you more things, not to give you marks but just to make sure you know. Coz sometimes you're so lost you don't know what to ask. If the demonstrator starts asking you what this happens, it can help you organise things. This is important.</p> <p>Reference 2 - 1.81% Coverage Apart from the thing that you do at home, there's not much communication with demonstrators. It depends on which. Some of them help you more, they ask more questions. Some others are kinda more relaxed. They're friendly but they don't push you so much. So you end up like... you're super cool but I don't really understand this.</p> <p><Internals\\Interview Data\\Interview 5> - § 2 references coded [2.39% Coverage]</p> <p>Reference 1 - 0.94% Coverage</p>	

<p>The experiment before this one was fine, I think. The experiment went quite smoothly. The demonstrator was helpful, but withhold information if they felt like we could work out ourselves. So that one went quite well.</p> <p>Reference 2 - 1.45% Coverage One of the demonstrators was quite helpful. I don't know her name. She did actually help me with some of the theory behind the molecules, describing how the programme worked. So that was interesting because no one had ever taken time to roughly explain how the programme works, did the calculations on the molecules and that was good.</p> <p><Internals\\Interview Data\\Interview 6> - \$ 1 reference coded [1.25% Coverage]</p> <p>Reference 1 - 1.25% Coverage There was a bit uncertainty with the setting that we used for running the scan. The demonstrator wasn't super sure either. I think the reference that he had was different from the lab manual.</p>	
<p>Postlab</p> <p><Internals\\Interview Data\\Interview 2> - \$ 1 reference coded [0.96% Coverage] Reference 1 - 0.96% Coverage H: So there was no investigation part in the lab last year? 2: No, you just followed the instruction. There was a bit of investigation aspect to the lab report I guess. But it depends if you want to go in depth with the report, if you want to look at the equations. It was not required by it. It only improved your mark.</p> <p><Internals\\Interview Data\\Interview 3> - \$ 2 references coded [1.10% Coverage]</p> <p>Reference 1 - 0.92% Coverage the write up was beyond reasonable. Obviously, I think 2 girls in my group wrote 5500 words. I wrote 3800. It took almost all Saturday and Sunday. There was 5 or 6 section points just for part 1 alone, and each one took an Excel table and a good chunk of theory about explaining the result. That was in part 1 and part 2 was exactly the same. It was just an excessive amount of work.</p> <p>Reference 2 - 0.18% Coverage they all agreed that this was really, really long. It shouldn't be that long.</p> <p><Internals\\Interview Data\\Interview 6> - \$ 3 references coded [2.47% Coverage]</p> <p>Reference 1 - 0.52% Coverage So many graphs at the end that it took longer to process than I had anticipated.</p> <p>Reference 2 - 1.23% Coverage Not really struggled with that. I just put out some tables and stuff from the last week session, the part one data, just to see the sort of match the trend you would expect, which it did.</p> <p>Reference 3 - 0.71% Coverage I had the articles when I was doing the second week and I could basically match the same trend that I expect.</p>	

7.7. Appendix G. Data Analysis (Part 2)

	NoS Aspects	Levels	Codes
VNoS	1. Empirical nature of scientific knowledge	Naïve	<p>Files\\Interview Data\\Interview 3.13 4 references coded, 5.62% coverage</p> <p>Reference 1: 1.10% coverage I'm not trying to differentiate other stuff or discriminate, but I think theory from science is always proven by experiments or something happens from nature. We have to show with our data or result, we have to prove it.</p> <p>Reference 2: 1.29% coverage Science, as I mentioned previously, some theories are contradicted later on, or re-evaluated. While art, at the time when it was produced, maybe people thought it was not special. But later on, after the artist passed away, maybe people think it was nice.</p> <p>Reference 3: 2.03% coverage H: What about the approach to science in comparison to art? 13: Maybe it's quite similar because when they paint or draw something, or when we want to investigate something in science, first we set up a plan, then we find a method. In art, they choose what they're going to paint with. In science we choose whether to use chemistry method or physics method. Then we go more deeply. We go into specific topics.</p> <p>Reference 4: 1.19% coverage Well, what they produce is quite different. Art, they produce paint, monument, or some structures. In science, in chemistry you produce some oily stuff, powder. They come up with some engineering. The form of the product is different.</p> <p>Files\\Interview Data\\Interview 3.11 3 references coded, 3.57% coverage</p> <p>Reference 1: 1.65% coverage I would say it is a discipline. Well, to be honest, when I think of science, I think about a group of disciplines. So, chemistry, physics, biology, maybe math (?) that have to do with different levels of life that surround us, like biology is looking into living organisms. Then chemistry looks at materials. And particles in physics, even like smaller particles. So, it's the discipline that studies everything.</p> <p>Reference 2: 0.36% coverage It's a procedure to discover something, or measure something and get a result of some sort.</p> <p>Reference 3: 1.56% coverage Obviously they are quite different, because as I said before, science is very strict and you try to find the truth and art is about your own truth and what you want to communicate and the reaction you want people to have looking at your art, and there's not much freedom in science. There's only like one answer we have to find out. It's not like what you think or what you like that answer to be like.</p> <p>Files\\Interview Data\\Interview 3.12 4 references coded, 3.45% coverage</p> <p>Reference 1: 1.41% coverage I did a course in philosophy last year. I did the Age of Enlightenment, Kant. And the recurring issue was a battlefield in metaphysics where someone says some things and others prove them wrong, and they some things back. This is never ending. There's no absolute conclusion. Which is why they can't make it a science. They can't make it physics.</p> <p>Reference 2: 0.18% coverage It's a test to find... like an absolute value.</p> <p>Reference 3: 1.18% coverage That's a good question. I don't know. I think it's a matter of interpretation. You could say that art is more creative in a way that it's generally done. Science is more learning and sticking to the rules, whereas art you can elaborate, bring a whole new thing, adapt. There's a lot more play.</p> <p>Reference 4: 0.68% coverage In a way that they both present something. So art would present some person's skills or concepts that they want to bring across. And science also presents concepts.</p>
		Transitional	<p>Files\\Interview Data\\Interview 3.11 4 references coded, 4.27% coverage</p> <p>Reference 1: 0.85% coverage So I would say it is based on research and facts, and you have to follow a scientific method. So you have to base what you say on findings and experiments, whereas philosophy is more about your opinion, your thoughts.</p> <p>Reference 2: 0.62% coverage</p>

			<p>a lot of things that science is about are not straightforward. You can't just see them. You have to think about ways to find out with different experiments.</p> <p>Reference 3: 1.25% coverage</p> <p>If you want to know the product of a reaction, you can try to guess it but then you have to actually perform that reaction, then analyse the product, and find out what it is that you get. Also for mechanism. You can't just know what the mechanism is. You have to do the experiment to understand how the reaction proceeds.</p> <p>Reference 4: 1.55% coverage</p> <p>So for climate change, there's so much evidence about the fact that it is happening. So Donald Trump could get a bunch of scientists who said that it is happening and they can try and get some sort of data that proves that it's not. But that means that you're ignoring so many other things, not taking them into account. Obviously that's not a good result that you're obtaining from your research.</p> <p>Files\\Interview Data\\Interview 3.12 3 references coded, 4.67% coverage</p> <p>Reference 1: 1.11% coverage</p> <p>Science is based on evidence and it can be tested over and over. And the same result comes out. It's a direct reflection of materials, states. It can't be rationally argued against, because of the evidence. So that's the main difference between physics and metaphysics.</p> <p>Reference 2: 1.89% coverage</p> <p>And that is what defines science from philosophy is that there is an absolute value in science, because you are measuring things that are kind of material. I also think that philosophy is more about thought. It's more of an art form in terms of thoughts. And it ties nicely with beliefs, something like that. And with religion, the main difference is evidence. Evidence in God, science would say, there's no evidence for God. Religion says you don't need evidence.</p> <p>Reference 3: 1.67% coverage</p> <p>H: After scientists developed a theory, do you think it changes?</p> <p>12: Yes, definitely.</p> <p>H: If the absolute value has been reached or concluded, then there will be no room for change?</p> <p>12: Well, that's where philosophy and science correlate. Because obviously our theories are constantly evolving. The current theory for an atom is not absolute. But there are some values that you can say... relatively absolute.</p> <p>Files\\Interview Data\\Interview 3.13 1 reference coded, 1.83% coverage</p> <p>Reference 1: 1.83% coverage</p> <p>Obviously, because opinion is just... what I think or what others think. I can say, I think this is true. But knowledge is not like opinion. It's totally different. I think knowledge is accepted concept. I think what the textbooks say would be called knowledge. They don't call it opinion. Author could say, this is my opinion. They cannot say, this is my knowledge.</p> <p>Files\\Interview Data\\Interview 3.9 1 reference coded, 1.35% coverage</p> <p>Reference 1: 1.35% coverage</p> <p>H: With all the development in science, do you think scientific truth exists?</p> <p>9: Well, I do think that it's not entirely instrumentalist, right? We don't think that we're just using this because it works. I do think that it relates to reality, in some fundamental sense. It might not be exactly right, but I would say I'm probably a realist in some sense, whether that's structural realism or ontological realism. A part of fundamental entity, I'm not really sure, but it's not arbitrary in that sense.</p>
		Informed	<p>Files\\Interview Data\\Interview 3.10 5 references coded, 6.81% coverage</p> <p>Reference 1: 1.77% coverage</p> <p>So, if you have an understanding of something, for example some mechanism that's accepted, that we know 100% that it's actually true, and then you have this new reaction that doesn't conform to the mechanism, so you can use this understanding from the old theory to understand why that reaction doesn't conform, or maybe you can propose an explanation into why it doesn't work and make a new theory, or new mechanism. So I think it's useful.</p> <p>Reference 2: 0.53% coverage</p> <p>One thing in which they're definitely different is experiments... the experimental method, which is used in science but not in art.</p> <p>Reference 3: 0.96% coverage</p> <p>I think the similarity is that people try to explain observations. So art might be trying to explain human nature or mostly focus on human and science... for example psychology also studies the human nature but in a different method than art</p> <p>Reference 4: 1.25% coverage</p> <p>I'm sure there's some group of opinions in science, but scientific knowledge is quite different in that it's supported by experimental data, whereas if you have an opinion, you</p>

			<p>don't have to have examples to support your opinion. So if you have an opinion that the Earth is flat, that is not really scientific.</p> <p>Reference 5: 2.30% coverage</p> <p>H: What do you think about... people who think climate change isn't real, like Donald Trump, who thinks that it's just a bunch of opinions?</p> <p>10: I don't think that's smart, lol. It's more a statement that he makes, which is more opinionated than let's say the theory of climate change, which has numerous data supporting that theory. There's definitely a large difference between his opinion and that theory, although there might be some calculations that support his 'theory' like the negative feedback or positive feedback, not sure which one, against climate change.</p> <p>Files\\Interview Data\\Interview 3.12 2 references coded, 3.98% coverage</p> <p>Reference 1: 1.27% coverage</p> <p>What is science, in your own words?</p> <p>12: [rather long pause] So... looking at the natural world and picking out different things that are correlated or the same every time...</p> <p>H: A pattern?</p> <p>12: In a pattern. Analysing them and coming to a conclusion. Also using those patterns and conclusions to produce something new.</p> <p>Reference 2: 2.71% coverage</p> <p>H: Do you think the development of scientific knowledge requires an experiment?</p> <p>12: Yes, because there needs to be evidence to back up theories.</p> <p>H: Any example?</p> <p>12: Structure and bonding. In Year 3, we've just done a tutorial about it. There's theories about molecular orbitals and their different energies. By testing the molecules, you can figure out where to put the energies in the energy level diagrams. So the diagrams are absolute. But the energy levels don't really look like that. It's probably more complex than how we're envisaging them. But the theory goes along with the evidence. So, you need experiments to get the evidence so you can make a theory.</p> <p>Files\\Interview Data\\Interview 3.14 3 references coded, 9.51% coverage</p> <p>Reference 1: 4.05% coverage</p> <p>We were talking about knowledge, field of knowledge, ways of knowing. There are different ways of knowing, and religion is one of them. It's a matter of how we approach and justify knowledge. How we form our thoughts and conclude that specific field. I would say for science it's the most straightforward because you can take 10,000 apples, drop them, and form a theory. You can justify what you say about apples. Whereas in religion, the way you justify knowledge is slightly different. You do have a common book that you refer to, but it's kinda open to interpretation. So I would say it's about who and how you use it. Because in science you have someone else, for example if you want to do an experiment on a certain molecule, then you use the same condition, same supplies, you can reproduce it in a way that you can verify what others have done. In religion you can't necessarily produce the same result.</p> <p>Reference 2: 2.28% coverage</p> <p>It's a part of scientific methods. You form a hypothesis, you observe a pattern, to form a theory. You have research questions that you want to prove or check. So you do an experiment to see if the theory is actually working. You do that by selecting some parameters, some could be constant and you can change some variables, and then you see if something is changing if you change the variables. So essentially an experiment is concluding whether pattern changes because you change one specific parameter.</p> <p>Reference 3: 3.19% coverage</p> <p>Well, definitely, because scientific knowledge is what we have done so far by experiments, maybe in the last 200 years. We can now recall by written literature. The first premise is still correct, that science based on data has to be reproducible to some extent. Just to confirm what is in the textbooks or to make data more concise, also for expanding it. For example, we can make new stuff like polymers. So in order to investigate their properties, how we can make new things, or the possibility for making a new machine such as NMR. In chemistry and physics it's all about developing techniques. For updating what we know, we have used experiments. I'd say all of the knowledge is confirmed by experiments.</p>
	2. Inference & theoretical entities in science	Naïve	<p>Files\\Interview Data\\Interview 3.14 1 reference coded, 1.10% coverage</p> <p>Reference 1: 1.10% coverage</p> <p>We are certain about 60-70%, at the same time, we have Heisenberg certainty saying that we'll never know where an electron is. We can think of electrons as a cloud. The visualisation of orbitals is captured in one specific time, in this context.</p> <p>Files\\Interview Data\\Interview 3.9 1 reference coded, 0.41% coverage</p> <p>Reference 1: 0.41% coverage</p> <p>I think almost any chemist thinks there's such thing as atom, we know there's a nucleus, there's electron. I don't think anyone disputes it at this point.</p>

		Transitional	<p>Files\\Interview Data\\Interview 3.13 1 reference coded, 1.72% coverage</p> <p>Reference 1: 1.72% coverage I don't think we are very sure about it, because atom is literally very small. We can only come up with hypothesis or theories. Since it's very small and they're like unknown world, I don't think scientists are very sure. They are trying to discover more about it, but I think there should be more to atomic theory. We still have more to discover.</p> <p>Files\\Interview Data\\Interview 3.10 1 reference coded, 0.59% coverage</p> <p>Reference 1: 0.59% coverage But... I think they're quite confident but I mean you have scientific data supporting the calculations and predictions so they're quite certain.</p> <p>Files\\Interview Data\\Interview 3.14 1 reference coded, 2.22% coverage</p> <p>Reference 1: 2.22% coverage That is more vague and up to readers' discretion. For living species, because they are complicated, multicellular organisms, it's more complex than just atoms. Think about cells, organs, organisms. When we talk this complexity, we already have so many different possibilities of how we can arrange them. It will be hard to talk about certainty because there's so many different patterns and variables. You could say this is a mammal and the other isn't, but that's basically all you can do.</p>
		Informed	<p>Files\\Interview Data\\Interview 3.10 3 references coded, 2.90% coverage</p> <p>Reference 1: 0.40% coverage 10: I mean, they can never completely sure because of the duality but I think they're quite confident Reference 2: 2.30% coverage H: What scientific evidence do you think scientists use to determine the structure of the atom? 10: Well there's always spectrometry, which provides evidence for the molecular orbital diagrams. So that's one way of supporting it. I mean, the vibrational spectroscopy or electronic spectroscopy... those data support the model. I wouldn't think there's a way of visualising and actually seeing an image of molecular orbitals as they're drawn, so they might not be certain about that. I don't think it's ever possible to 100% say that that's how the orbitals look like. Reference 3: 0.20% coverage you can never 100% sure about anything in science</p> <p>Files\\Interview Data\\Interview 3.12 1 reference coded, 3.83% coverage</p> <p>Reference 1: 3.83% coverage H: How certain are scientists about the structure of atom? 12: I don't know. I wouldn't be able to tell you. I don't know the scale. We are at a certain level of certainty, but that scale could be to an infinity... H: Or to 100%? Are we going to be 100% sure about the structure of atom? 12: No, I don't think so. H: Why? 12: Because from a philosophical point of view, I don't think we're 100% certain that what I'm saying now is the way I'm saying it. There's always a way that I'm interpreting what I'm saying. So we could be more accurate in our description of what the things look like but I don't think we'll ever get an objective feel of what it really is. H: That's a way of looking at it. 12: So, the representation of an atom is a way of looking at an atom and the image that I have of you is a way that I can look at you. But in both ways, there's a lot of inaccuracies there. I don't think I can ever get 100% accurate view of anything. Even like a bottle or anything.</p> <p>Files\\Interview Data\\Interview 3.11 1 reference coded, 2.16% coverage</p> <p>Reference 1: 2.16% coverage I think we have a good knowledge today, but I also think that it's so abstract and complicated that you can't just teach it to high school kids. You have to sort of give them an easier thing to represent it. But obviously you can go into physics and study it from a different perspective and it's just not a little ball with a nucleus and electrons spinning around it. I think it's just a way to... coz like human finds it easier to visualise things. So even for me, for example, it's easier to think about it that way than some abstract quantum mechanics.</p>

	3. Nature of scientific theories	Naïve	<p>Files\\Interview Data\\Interview 3.11 4 references coded, 4.23% coverage</p> <p>Reference 1: 1.44% coverage Sometimes. Like there are paradigm shifts. Obviously it's not so common, because they do experiments and they think what they found is the truth. And then once in a while, maybe there's something that they didn't look at, like it happened with physics for example, and everything changes. But I would say most of the knowledge we have is probably quite accurate.</p> <p>Reference 2: 0.77% coverage I didn't really say that knowledge develops. I think we, like, accumulate knowledge and sometimes we found that some of that knowledge is not accurate so we replace it with some new knowledge.</p> <p>Reference 3: 1.45% coverage H: Why do you think theories change? 11: I would say probably one of the big things is the development of technology, so obviously you formulate theories using the technology that's available to you, but the more advance technology, the more we can for example have closer looks at things like atoms and hence we can gain a better knowledge, like closer to the truth.</p> <p>Reference 4: 0.57% coverage H: So there's no 100% certainty? 11: I think for some things there are. Like if there's 100 people doing an experiment and they get the same result</p>
		Transitional	<p>Files\\Interview Data\\Interview 3.10 1 reference coded, 2.25% coverage</p> <p>Reference 1: 2.25% coverage H: With the current development in quantum mechanics, do you think our understanding of how atoms look like radically changed? 10: I mean quantum theories definitely change our understanding of energies of different orbitals which allowed much deeper understanding to what was known before. But in terms of an actual visualisation of the atoms with the quantum theories and orbitals, yeah I think it radically changed but the visualisation with just the bonds, the structures without the actual molecular orbitals, I don't think that has changed much.</p> <p>Files\\Interview Data\\Interview 3.9 2 references coded, 0.44% coverage</p> <p>Reference 1: 0.12% coverage they changed until it's empirically correct</p> <p>Reference 2: 0.32% coverage it's difficult to talk about the capital T, Truth, when you have some sort of incommensurability between the theories</p>
		Informed	<p>Files\\Interview Data\\Interview 3.10 2 references coded, 3.28% coverage</p> <p>Reference 1: 2.17% coverage I think it's about to change. I mean, most theories eventually... as the understanding progresses... although the theory itself might stay the same, they might just become a new theory, might just evolve. So a new theory might replace the old theory, or the old theory might improve based on new data. The new theory might be used together with the old theory. So for example there's this valence bond theory and the other theory, I can't remember what it's called, we still use that theory although we know there's some inherent mistake in it.</p> <p>Reference 2: 1.11% coverage Without the theories we wouldn't have an understanding of science, I mean of the subject of study. Using these theories as a basis knowledge, you can then maybe do some more research. And based on this knowledge you can... I mean they are evolving but you can use this knowledge too.</p> <p>Files\\Interview Data\\Interview 3.13 1 reference coded, 2.04% coverage</p> <p>Reference 1: 2.04% coverage I think theories always change when there's a new theory. For example, people used to think that Earth was flat, but now we know that it's round. Since there's a lack of knowledge, even though science is much developed now, we still have to look forward, we have to know more. And due to this, I think some people believe this one, but later on when there's a new discovery, this one is taken over by new theories.</p> <p>Files\\Interview Data\\Interview 3.9 8 references coded, 4.62% coverage</p> <p>Reference 1: 0.10% coverage I think that's quite often in the past</p>

			<p>Reference 2: 0.19% coverage in physics we went from Newtonian mechanics to Einsteinian mechanics</p> <p>Reference 3: 0.44% coverage It's a classical example in chemistry. In 18th century, later on we adopted in chemistry. In the 20th century it changed again with the rise of quantum mechanics.</p> <p>Reference 4: 0.41% coverage most of the theories in the past have been wrong, because eventually they got overturned by new theory. So, what is the likelihood that we are now correct?</p> <p>Reference 5: 0.55% coverage not all theories have completely been overturned. We know now that Newtonian mechanics is not entirely correct, but we still use it, we still keep it. We say it's a limiting case of Einsteinian mechanics.</p> <p>Reference 6: 2.06% coverage I suppose yes in that quantum mechanics is not our final theory. There's still undeveloped issues and most of the things that chemists work with is approximation anyway. And quantum mechanics isn't entirely consistent with relativity theory either. So one of them must be at least developing. I don't think we're at the end. But I think probably it's quite tempting to think that because some parts just feel very established that it might be tempting to say, well we accept that and that's the state of the art. At least the foundation looks kinda set, right? But maybe some of the things will change. Not in any fundamental sense that we don't have to talk about atoms anymore but maybe in the sense that... as I said... we move from one notion of the electrons to another one.</p> <p>Reference 7: 0.71% coverage H: Is it like fine tuning of what we already know? 9: In philosophy of science we usually differentiate between the development within the framework and the paradigm change. I don't want to go to predictions about paradigm change. I don't think I can assess that.</p> <p>Reference 8: 0.16% coverage H: It's always contestable in science, I suppose. 9: Yeah.</p> <p>Files\\Interview Data\\Interview 3.14 2 references coded, 4.46% coverage</p> <p>Reference 1: 2.83% coverage For sure hypotheses change. You can't form such a hypothesis that can't be broken, because otherwise it just doesn't go by laws of hypothesis. Theories go somewhat the same way. Theory, I would say, is a concept of thought, a linkage system of filter of how you would like... imagine you have a set of data, some kind of scattered, graph, and that is how you explain that pattern, that trend. And by theory you mean that you filter it because you see causality. So you can put this trend together. And if your theories or predictions or the laws, whatever you call them, work together and explain everything, you could say that they work.</p> <p>Reference 2: 1.63% coverage Scientific methods' underlying assumption is that you try enough and it would be working. But you have to consider that it can still change. If you're talking about the same, gravity, yes it works for big objects, but when we talk about very small objects like in quantum physics, it's quite different. So they have to say, this theory applies only to big objects.</p>
	4. Scientific theories vs laws	Naïve	<p>Files\\Interview Data\\Interview 3.10 4 references coded, 3.84% coverage</p> <p>Reference 1: 0.53% coverage H: Is there a difference between a scientific theory and law? 10: I don't think so. I mean the laws are based on theories... aren't they?</p> <p>Reference 2: 1.04% coverage Well there's this... I think it's a law... for the electronic transition that the spin's forbidden. So the spin must not change during that transition, and that's based on quantum theory, I believe. So that could be one. I think a law is just an outcome of a theory.</p> <p>Reference 3: 0.94% coverage just from the words... it has a connotation of law being more definite than a theory, but if you really think about it I think theoretically a law might be the same as a theory but in practice, maybe a law sounds more definite than a theory.</p> <p>Reference 4: 1.33% coverage I think there's a difference in that you don't really have to understand the theory as long as you know the law. So in that terms I think a law might be higher. For example there's more theories to explain the law. The most important thing is the actual law, not the theory, although the theory might help you understand more or expand.</p> <p>Files\\Interview Data\\Interview 3.13 2 references coded, 1.47% coverage</p> <p>Reference 1: 0.85% coverage As far as I know, I think law is never changing. So scientists can come up with a theory but this can be contradicted by another theory. But I think laws are like firm and set.</p> <p>Reference 2: 0.62% coverage</p>

			<p>Thermodynamics law. It never changes; it's permanent. I can come up with any theory and other people can say that's wrong.</p> <p>Files\\Interview Data\\Interview 3.14 2 references coded, 2.48% coverage</p> <p>Reference 1: 0.86% coverage You call them laws because they cannot be changed. If you change them, then you are witnessing a severe punishment. Laws are just like rules in games, if you break them, you are disqualified.</p> <p>Reference 2: 1.62% coverage we call it law because it has more power than just guidelines that a theory provides us. Probably because law doesn't have substitutes? Or maybe law has less plausible substitutes. Maybe we can say that laws provide 95% explanation of natural cases, whereas theories provide 65%. Law is more superior in terms of efficiency of predicting the world around us.</p> <p>Files\\Interview Data\\Interview 3.12 1 reference coded, 1.78% coverage</p> <p>Reference 1: 1.78% coverage H: Difference between law and theory... 12: Yeah. Scientific law is the thing that's kinda absolute, you can't argue against it. H: Any example? 12: I don't know, like Newton's law of motion. H: OK, whereas a theory... 12: A theory is like... you can develop it. H: Is there any hierarchy between theory and law? 12: Yea, I think the law is probably better. I mean, you got somewhere to depart from, because it's absolute, and you can stand on that law.</p>
		Transitional	<p>Files\\Interview Data\\Interview 3.10 1 reference coded, 1.14% coverage</p> <p>Reference 1: 1.14% coverage The example you gave was thermodynamics... I mean there might be a difference where a law, in terms of thermodynamics, comes from... there might not be an explanation of it. I mean there might be different theories on why the law is true. And law is just an observation of what takes place.</p> <p>Files\\Interview Data\\Interview 3.11 2 references coded, 2.32% coverage</p> <p>Reference 1: 1.30% coverage When I think of scientific laws, to me that sounds like something that is a foundation of everything else, and theories have to obey those laws, coz they're like basic. Otherwise you could go on like in too many directions. So I would say the laws are like the really fundamental pieces of knowledge on which everything is based.</p> <p>Reference 2: 1.02% coverage H: Can you give me an example of that? 11: Like the laws of thermodynamics. H: So we don't call it the theories of thermodynamics? 11: No, it's the first law, second law, and so on. So the difference is that scientific laws are constant whereas theories change.</p> <p>Files\\Interview Data\\Interview 3.14 1 reference coded, 1.44% coverage</p> <p>Reference 1: 1.44% coverage Scientific theory... it has been confirmed that it's working. At the same time, it's called theory because it doesn't explain everything. Just like molecular orbital theory. It doesn't cover everything. Theories are guidelines, in a sense. They predict that things usually go this way, but they're not fully perfect.</p>
		Informed	<p>Files\\Interview Data\\Interview 3.9 4 references coded, 3.26% coverage</p> <p>Reference 1: 0.58% coverage Well... law is... sort of ill-defined... in a way... somewhat misleading term, right? Because we always have the association from legal things that laws govern. But maybe that's not exactly what we mean by laws in science.</p> <p>Reference 2: 0.51% coverage law is something that... either just describes regularity. There's some issues with that because some of those regularities aren't necessarily true, and some are just intentionally true.</p> <p>Reference 3: 0.85% coverage So maybe you have to take that into account in your definition of a law. But I suppose I would take some sort of Humian perspective in a sense that law is regularity as opposed to, I suppose, dispositionalism, things are and do act in a certain way. I think it's difficult to really be satisfied with either explanation.</p>

			<p>Reference 4: 1.33% coverage</p> <p>Theory... how's theory different. Intuitively I would say the term is definitely not the same in that theories describe more of an overall framework, whereas laws might be something that underlies the theory. I'm thinking whether that needs to be the case. Whether every theory has laws underlying it, but some do certainly. So just how we employ the term rather than... we talk about N-O theory rather than molecular laws. Laws are underlying things we employ to something like thermodynamics.</p>
	5. Creativity & imagination in science	Naïve	NA
		Transitional	<p>Files\\Interview Data\\Interview 3.12 2 references coded, 3.09% coverage</p> <p>Reference 1: 2.15% coverage</p> <p>You have to be very good to use your imagination. Obviously you're using different rules and playing with that. You use your imagination to come up with the solutions. I think if you have to come up with new theories, using your imagination.... I think all these great scientists like Einstein or Stephen Hawking, they were supposed to be good at using creativity and imagination. H: What about practising scientists in general?</p> <p>12: I don't think so. I don't know. Maybe I'm wrong. I'd like to be wrong, but I really don't think so.</p> <p>Reference 2: 0.94% coverage</p> <p>H: Do you still think practising scientists use their creativity and imagination?</p> <p>12: I don't really know. I mean, if they have to come up with their own experiment or investigation, they probably use creativity and imagination.</p> <p>Files\\Interview Data\\Interview 3.13 1 reference coded, 0.86% coverage</p> <p>Reference 1: 0.86% coverage</p> <p>H: What about after data is collected, do you still use them in science?</p> <p>13: I think we still do. How you present your data, you can be creative, to be better than other people.</p>
		Informed	<p>Files\\Interview Data\\Interview 3.10 5 references coded, 5.07% coverage</p> <p>Reference 1: 1.29% coverage</p> <p>They probably have to be creative in order to explain data, for example the data was not expected, which very often happens for various reasons. When I did an experiment in biology on growing algae at different temperatures, I had to explain why the data was zig zag, so no trend. So I had to be creative in explaining that.</p> <p>Reference 2: 0.85% coverage</p> <p>During the data collection, I think they still have to be creative in order to... for example just in the method, so trying to figure out ways how to arrange an experiment so that there's no air in the reaction vessel.</p> <p>Reference 3: 0.48% coverage</p> <p>They might want to use imagination to see how the experiment would go and to see if there's a potential problem in that.</p> <p>Reference 4: 1.07% coverage</p> <p>H: You can also zoom out to other field of science. Astronomy or astrophysics perhaps?</p> <p>10: I'm sure there's a lot of calculation involved. If you're studying black holes and you don't know what happens when something enters the black hole, that's a typical example.</p> <p>Reference 5: 1.38% coverage</p> <p>H: Yeah, has someone ever seen a black hole?</p> <p>10: I'm sure there's a lot of imagination in thinking what might happen, when it's so far away and it's practically impossible to see what's happening. So if you imagine a big star that is tens of thousands of times the size of the sun, you have to use your imagination to imagine what might happen around.</p> <p>Files\\Interview Data\\Interview 3.11 2 references coded, 2.40% coverage</p> <p>Reference 1: 1.08% coverage</p> <p>I think that could be useful, because sometimes if you have to find something that you have no idea about, trying to imagine possible things could be good, because if you could get from the data that suggests something that you imagine, that could be a way for you to find out.</p> <p>Reference 2: 1.32% coverage</p> <p>And creativity as well, because sometimes if there's something that's really hard to find out, and people have been trying to do the same experiment for a long time, sometime you need someone who comes with a different idea on how to investigate certain things, and that could be the right way to finally solve the certain question.</p> <p>Files\\Interview Data\\Interview 3.13 1 reference coded, 1.48% coverage</p> <p>Reference 1: 1.48% coverage</p> <p>I think science always involve creativity and imagination, because for example from our experiment Part 2, we had to design our own experiment. Likewise, when we write</p>

			<p>dissertation or paper, we have to find something new that others did not find yet. And I think that's related to creativity.</p> <p>Files\Interview Data\Interview 3.14 2 references coded, 2.47% coverage</p> <p>Reference 1: 1.22% coverage Definitely, yes. If your hypothesis was proven wrong, you have to understand it. When you change a variable in an experiment and see how other variables are changing, you have to be creative enough to explain why it happens. So it's useful when you have to explain your data</p> <p>Reference 2: 1.24% coverage Imagination is even more. You need to think of new breakthrough ways to see if a theory is wrong. For example, people thought the Earth was flat with three big elephants because they couldn't see any curves. So, obviously you need some imagination to come up with a round earth.</p> <p>Files\Interview Data\Interview 3.9 7 references coded, 7.91% coverage</p> <p>Reference 1: 1.29% coverage One way of looking at the answer is how we use the terms metaphorically, right? We talk about work in the lab, maybe that's sort of an art because it requires some sort of intuitions sometimes. It's not always super regular, but maybe it feels a bit like a craft that you're learning. Maybe that's true for some artists. Maybe generally that's not some regular sense. It's something that you learn with intuitions and so on. So maybe we use that term, art, metaphorically sometimes.</p> <p>Reference 2: 0.30% coverage 9: You wouldn't really employ the other way around very often. H: You mean like whether art is scientific? 9: Yeah.</p> <p>Reference 3: 1.64% coverage H: Think about music, for example. Do you see science in music? 9: That's a good example. I think there's mathematics underlying musical theory. But then again, it's probably two separate issues, because in making art you don't necessarily follow very rigid framework. I guess in music maybe you use, because harmony and so on, but visual arts maybe less so. Music is probably a good example of how they can be similar in some sense. Natural science primarily relies on mathematics. In some sense music can be encapsulated or can be described in mathematical as well. So you got an example how they're similar.</p> <p>Reference 4: 1.25% coverage Maybe there are two issues. One is how they're conceptually the same or similar, and then how they're practically or maybe sociologically... how we conduct science. How they're then similar or dissimilar. Conceptually I have trouble answering that on the spot. Maybe you have to differentiate between different arts and maybe different science. And then in terms of how they're conducted maybe nowadays science tends to be collective enterprise than most art.</p> <p>Reference 5: 0.68% coverage Creativity is probably the more narrow concept, but even that... I would certainly say yes they do use, because even once you have your data, you still have to know what it tells you, what kind of analysis you have to do. That's the creative aspect of science.</p> <p>Reference 6: 0.97% coverage Imagination seems like the more fundamental concept. Imagining underlines all thought about something that's potential. So what could I do with it. You have to imagine what you could do with it, right? So in a sense, whenever you plan to take something in a certain direction, or you have to do certain things with the data, or whatever, you use your imagination.</p> <p>Reference 7: 1.78% coverage H: When I think about quantum theory, for example, to me it's very abstract, somewhat vague. It's difficult to even try to comprehend. 9: It's very abstract, indeed, but maybe it's not vague, necessarily. But I do agree with you that you can't really visualise. H: Maybe that's where imagination takes place? LOL 9: LOL. Trying to remember, maybe it was Bohr who said that but I could be wrong.... You don't really understand it, you get used to it. So that's probably part of it, because some of these things are just so different from everyday life that we can't comprehend them in some intuitive sense, but we have to extract from the method derived from mathematics.</p>
	6. Subjectivity in science (theory-ladenness)	Naïve	<p>Files\Interview Data\Interview 3.11 2 references coded, 2.18% coverage</p> <p>Reference 1: 1.52% coverage Well obviously because we don't have too much information to come up with one theory, coz otherwise everybody would have to agree. So there's not enough evidence. They have to make hypothesis. They can think of the climate of the earth back then and things like that. So I think it's because we don't have enough evidence to be sure, so there's more room for different possibilities.</p> <p>Reference 2: 0.66% coverage we wanna find the one truth like what happened. But I think as long as you don't say this is what happened, but this is what might have happened, it's allowed in science.</p>

			<p>Files\\Interview Data\\Interview 3.12 1 reference coded, 1.04% coverage</p> <p>Reference 1: 1.04% coverage Maybe the data can indicate one way or the other and there's no way to distinguish between the two? So it could be from the volcanoes or meteorite. Maybe it's taken such a long time that the evidence has deteriorated and you can't draw the right conclusion?</p> <p>Files\\Interview Data\\Interview 3.14 2 references coded, 5.05% coverage</p> <p>Reference 1: 2.62% coverage Either way, both of them may have caused big explosion, poisonous stuff, tsunami, earthquake. Both actually make sense, and we're talking about 65 million years ago anyway. It's kinda hard to decouple all this data. We could theoretically make a computer simulation, but that would be based on what we know right now. The atmospheric composition back then was probably different. Piles of potassium nitrate might have existed around the explosion but they're not there anymore. Both of the stimuli would leave the same residue, it'll be hard to distinguish which one is which.</p> <p>Reference 2: 2.44% coverage H: But what can you say about these groups of scientists coming to different conclusions? R: They looked at different areas... H: Does it mean of them is wrong? Or maybe both are wrong? R: Well that's hard. I'll have to be diplomatic lol. I suppose both of them are correct about something, given the reasonable explanations of what has happened. They were both correct about what caused the death when it comes to poisonous air, tsunami, etc. But what caused this natural disaster could be contestable. So, I guess they're correct but not fully.</p>
		Transitional	<p>Files\\Interview Data\\Interview 3.9 2 references coded, 2.06% coverage</p> <p>Reference 1: 1.23% coverage H: That's a good point. What about objectivity in science? The statement that science is evidence-based, whereas art is more liberal. 9: Again, I can think of two things. One is that art doesn't make a claim quite exactly or unfalsifiable in the way that science usually does. So in that way it would be odd to ask an artist to say, oh... how's your painting falsifiable? How can I say that this is objectively true? It's not a kind of thing that's objectively true. Reference 2: 0.83% coverage Probably that's not possible once you conclusively prove something. Well, prove is a strong word, but once you conclusively show something, you can't dispute it anymore. So once you conduct experiments that no one can reasonably object to and show one thing to be true, you can't claim both things anymore.</p>
		Informed	<p>Files\\Interview Data\\Interview 3.10 2 references coded, 2.97% coverage</p> <p>Reference 1: 0.97% coverage I mean it's possible that the data can be explained by two theories. I'm not sure which one would be the more true one, but they might both be equally valid, given the data, whereas some geological features might be explained by both theories. Reference 2: 2.00% coverage I'm sure there's uncertainty in dating of the data where it might be unsure when the last dinosaur actually lived, where the data is limited, given the fossils. And I'm sure there's also a point of not just the data they worked with, definitely, because I'm sure not all researchers working on that have all the data available. They might be just focusing on some. So if there's some fossils in Germany that support one theory, the scientists in Germany might be more pro to one theory than the other.</p> <p>Files\\Interview Data\\Interview 3.9 3 references coded, 5.02% coverage</p> <p>Reference 1: 1.15% coverage Another challenge is the values that underlie your theory choice. So what kind of theory do we employ. Because that has to be linked to subjectivity, right? Because we want our theory to be internally and externally consistent. We want them to be as simple as possible. Those are the things that you can link to this objectivity. But that's also being challenged in that some people say maybe we should be ontologically diverse. Reference 2: 0.89% coverage H: Opinions... everyone has one, whereas scientific knowledge isn't. You can't say that two opposing things are true. But people can hold opposing opinions. So you can go more into details about what we mean by knowledge, but that's the easiest way to dismiss that. Reference 3: 2.98% coverage H: The reason why I was teasing you with that is because especially now in the age of social media, people always have opinion about something; about vaccination, about evolution, right? Evolution is just a theory, or vaccination causes autism. And they would say, I have done my research... by watching YouTube videos, lol. What do you think about that? 9: If they say my opinion is that, then you have to differentiate between pseudoscience... some people claim that what they do is science but they're misusing the concept in some</p>

			<p>way. They're not doing science properly. Then you come up with supposedly scientific system but there's no such thing that's not easy to rebuttal in a sense that you examine their flaws and you point them out and then you may or may not have been convinced. Then you have a case of pseudoscience. And there's non-science, broadly speaking; things that make no claim to be scientific, but also not pseudoscience because they're not pretending to be science. And there's other thing that is... BS because they don't care about the truth. That's the most dangerous, I think.</p> <p>Files\\Interview Data\\Interview 3.9 4 references coded, 6.14% coverage</p> <p>Reference 1: 1.77% coverage H: Well, this is probably an assumption of laypeople that when they think of science as something objective, whereas art is subjective. Do you agree with that? 9: Oh ya, that's the second point. I would probably agree that science is generally objective. I wouldn't say it's the whole truth and it's not the end of it. There can't be such a thing. There's probably, within science, there's a part there's several aspects that's sociologically... who funds science and so on, what research is being conducted. So that can be maybe a challenge to objectivism because all your money comes from one side or resource and they're probably one thing that can claim that.</p> <p>Reference 2: 1.23% coverage H: To what extent do you think subjectivity is... not only allowed but also practised in science? 9: Maybe in what you focus on. Maybe the principles or the underlying values are mostly shared. But maybe you can still say, well this interests me more, that's what I want to focus on. Sometimes in the way you're doing things, such as two explanations that boil down the same thing. Some people still think one explanation is more intelligible than the other.</p> <p>Reference 3: 1.01% coverage And maybe without knowing much about the subject matter, about the example you just told me, I would say that's probably the case where no conclusive experiments like that have been done yet. Or there's insufficient agreement about how to interpret your experiment, because you can adopt different theories, different concepts. Then you arrive at different conclusions.</p> <p>Reference 4: 2.13% coverage H: Do you think for most phenomena that we know so far, for example about germs and diseases, are there more agreements or disagreements within the scientific community itself, when it comes to interpreting data from scientific experiments? 9: Maybe it's wrong but you tend to pay more attention to disagreements. H: Is that because it's what makes science keep developing? 9: Yeah, for sure. But you don't always dispute the others' work or theories. That's not the only way science advances, right? Within one paradigm you can go to different directions. Some journals published in Nature and we usually agree that what they found is correct. They're reviewed and we think they conducted their research up to a scientific standard, so there's an agreement about that being legitimate.</p>
	7. Social & cultural influences	Naïve	<p>Files\\Interview Data\\Interview 3.11 3 references coded, 4.67% coverage</p> <p>Reference 1: 1.45% coverage I would say it's universal, because it's based on evidence, not just some thoughts and opinions. So when you talk about evidence, evidence is just the same regardless of your cultural upbringing or religion or whatever, and that's why scientists from all over the world can collaborate to work on the same thing. Because it's not a social science, it is universal.</p> <p>Reference 2: 1.65% coverage I feel like science and religion are very different, and you shouldn't mix the two. I think you can be religious and have faith but still think that God didn't create the world. It was the Big Bang. And I also think that if you're a scientist, you should be rigorous and you should only base your work on evidence and experiments and facts. You can't let things like religious beliefs interfere with what you're doing.</p> <p>Reference 3: 1.57% coverage I definitely think that science can be a tool that politicians can use to meet their own goals. It has been done during World War II, Nazi Germany, and so on. But that's not real science because you're not just trying to find out something. It's like you already know what you want to prove and you're finding ways to prove that that is the thing you want, even if you don't follow a scientific method.</p> <p>Files\\Interview Data\\Interview 3.12 1 reference coded, 1.01% coverage</p> <p>Reference 1: 1.01% coverage I think it should be universal. Religion is more infused with social and cultural values. I think science deviates from that. It can be more trusted in telling the truth, because the truth is sometimes different from social and cultural values.</p>
		Transitional	<p>Files\\Interview Data\\Interview 3.10 4 references coded, 6.62% coverage</p> <p>Reference 1: 1.73% coverage It's hard to imagine a chemistry that reflects the social and political views. If you want to make a new drug, how could that be... I mean surely there's some political influence where you might be discouraged to find a new antibiotic because it's very expensive to actually</p>

			<p>bring it to market, and it's not economically beneficial as make a new drug against heart problems, where you have to take it throughout the rest of your life.</p> <p>Reference 2: 0.83% coverage</p> <p>I think it's different in scientific fields where there's more room for more influence than others. So if you work at a university, you're not influenced by some of your beliefs or other external factors.</p> <p>Reference 3: 2.04% coverage</p> <p>Although of course there's still some influence where there's trend in science. Or electorate recently showed us that there's a survey of scientists which solvent they believe is the future and it was pretty evenly spread but then there was another survey asking what they're actually researching, there was a more disproportionate belief where many more work on ionic solvent. Those that believe that is the future solvent. But I'm not sure how much that is influenced by social and political values.</p> <p>Reference 4: 2.02% coverage</p> <p>10: That could actually definitely reflect the science in a heavily religious country might be different from an atheist country. Or when research is taboo from some other reasons. For example, the research on... what is it called... impregnation?</p> <p>H: Artificial insemination you mean?</p> <p>10: Yes. Artificial insemination might be discouraged in religious countries. I'm sure there are more examples. But it depends on the subject where some are more universal, some are more influenced by social factors.</p>
		Informed	<p>Files\Interview Data\Interview 3.14</p> <p>1 reference coded, 3.10% coverage</p> <p>Reference 1: 3.10% coverage</p> <p>Yes and no. Another question would be... did human invent maths? Or did we discover maths? Was the integral there before? For maths maybe it's universal. Historically, we know that there were people who tried to twist science. For example, in 1930s someone claimed that one race was better than the other races, justified by the size of skulls. Or, some data from 1970s that cannabis is a gateway to drugs. Let's make a war on drugs. Yes, we have uniform, universal facts, but it's how we shape them that matters. Science is universal, unless if it doesn't confirm, then it's conditional. Just like statistics. There's a big lie, there's statistics. To some extent, you can apply it to science.</p>
NoS in lab	Students' perceived changes in views and understanding of NoS		<p>Files\Interview Data\Interview 3.10</p> <p>4 references coded, 3.63% coverage</p> <p>Reference 1: 0.84% coverage</p> <p>was aware even before that if you follow one set of instructions, one person might end up with different data than you. Although the instruction might be very specific, there might be some ambiguous things.</p> <p>Reference 2: 1.63% coverage</p> <p>Maybe I become more aware that it's necessary to keep your integrity about the data because there's always some bias where you try to make an experiment work. For example when you're not sure if the melting point is 52 or 53, you might choose a value that is expected of the experiment. So you have to keep yourself from that bias. So you might want to actually repeat the experiment or repeat the measurement.</p> <p>Reference 3: 0.74% coverage</p> <p>Maybe I also become aware that sticking to the procedure might not be necessary to the reaction. You can modify. You don't have to be stressed about adhering strictly to the procedure.</p> <p>Reference 4: 0.42% coverage</p> <p>H: Do you think there was enough room for that?</p> <p>10: Well I think so. As long as you mention that in the report.</p> <p>Files\Interview Data\Interview 3.11</p> <p>2 references coded, 3.72% coverage</p> <p>Reference 1: 1.81% coverage</p> <p>For sure. Firstly because I feel like when you're in high school or even before science was a lot more simplified, and then we you come to the university the things turned out to be a lot more complicated. And you also appreciate how hard it is come out with some knowledge. You have to go through a lot of experiments. It takes a lot of time and work and you have to plan them. So it's not straightforward to gain all the knowledge than what we learn from textbooks.</p> <p>Reference 2: 1.91% coverage</p> <p>That's the practical side of my course, so I'd say quite a lot. Because compared to high school where we did trivial things in the lab, what we do here are some of what scientists do today. So people publish papers and do important research. They do the same things to do, the techniques that we're learning. So you can realise how powerful these tools, techniques, the different machines that we use to actually make a difference, and discover something that's really meaningful.</p> <p>Files\Interview Data\Interview 3.12</p> <p>1 reference coded, 0.72% coverage</p> <p>Reference 1: 0.72% coverage</p> <p>H: Do you think your view of science has changed due to lab?</p> <p>12: No.</p> <p>H: How did you see yourself when you started this degree?</p> <p>12: Well, I thought science was the study of real things.</p> <p>Files\Interview Data\Interview 3.13</p> <p>2 references coded, 4.75% coverage</p>

		<p>Reference 1: 2.07% coverage That's a very profound question. Actually yes. One thing comes to my mind immediately is that the field of science is a lot bigger than I thought. I thought science was just one topic you learn in the undergraduate level. I could even master everything. But after I study for 3 years in chemistry, I think science is a lot bigger. And there's far more knowledge and theories I need to study to even master chemistry.</p> <p>Reference 2: 2.68% coverage H: Can you attribute that to lab? 13: Yeah, absolutely, because before studying chemistry level in high school, we only studied concepts. We did not learn about intermediate. We did not learn about catalysts, or pressure temperature. But in the lab, we know that we have to put this at a certain pressure temperature. We know all this complex condition to synthesise. I think these lab sessions changed my view of science. Lectures are quite similar to classes in high school. Labs are totally different. It's really helped me a lot.</p> <p>Files\\Interview Data\\Interview 3.14 4 references coded, 3.18% coverage</p> <p>Reference 1: 0.88% coverage In the first year, they gave you the procedure and you just had to do it. So you dealt with something specific. Whereas now in third year, it's more about using and developing that, which is harder.</p> <p>Reference 2: 0.41% coverage When you interpret your data, now you know well that you have to think about it, be creative.</p> <p>Reference 3: 0.59% coverage When you come out with different result, it teaches you how even in science not everything is perfectly replicable in the same way.</p> <p>Reference 4: 1.30% coverage I understood how subjective, how much science relies on execution and control of the execution. Or mastering the experiment, simple lab techniques, the reproducibility of your data, which can sound ridiculous. For example, the way you hold the flask could determine your experiment.</p> <p>Files\\Interview Data\\Interview 3.9 5 references coded, 2.95% coverage</p> <p>Reference 1: 0.39% coverage It's difficult to pinpoint because it's certainly not the kind of thing that fundamentally changed what I believed about theory, for example.</p> <p>Reference 2: 0.37% coverage I don't think laboratory experiments really relate to that kind of thing. If anything, it changes your views about scientific practice.</p> <p>Reference 3: 0.68% coverage I don't think there's been a change. I do think I'm reflective in terms of labs. And I think most undergrad labs, at least while you do them in the lab, don't require much of imagination. Maybe in how you assess the data later, or when you write your report.</p> <p>Reference 4: 0.60% coverage when you're stressed during lab sessions, you follow it like a recipe, but that doesn't change my view on science that I think something specific to undergrad experiments I designed to illustrate some concepts of the course</p> <p>Reference 5: 0.91% coverage H: Is it perhaps the case that you now see some nuance in the way you view and understand science? 9: Maybe, in terms of nuance, I don't think I arrived here thinking that science was absolute truth, but seeing department from inside, how research is being conducted. This kind of learning where you always expand on what you've learnt before</p>
	Prelab & NoS	<p>Files\\Interview Data\\Interview 3.10 1 reference coded, 0.96% coverage</p> <p>Reference 1: 0.96% coverage H: Any of that you think has influenced your view on some aspects of science that we have just discussed? 10: I'm not sure. I mean the instructions on how to use spectrometers, how to properly use the pipette, although that wasn't necessary.</p> <p>Files\\Interview Data\\Interview 3.11 1 reference coded, 1.65% coverage</p> <p>Reference 1: 1.65% coverage It depends on the prelab because some of them are very silly quizzes. So you just have to read the procedure and they're like how dangerous the substance can be, and you just copy what's written in the manual. Especially this year in organic chemistry, for example, the experiments are a lot more complex, the things we've never done before. So you really need to understand what it is that you're going to do in the lab.</p> <p>Files\\Interview Data\\Interview 3.13 1 reference coded, 1.59% coverage</p> <p>Reference 1: 1.59% coverage Prelabs actually didn't really affect me or influence my view of science. They were very good source of learning though, because there were many apparatus and equipment that you don't really see normally outside physical labs. By watching prelab, I learn how to deal with how to control or handle those equipment.</p> <p>Files\\Interview Data\\Interview 3.14 1 reference coded, 0.75% coverage</p>

		<p>Reference 1: 0.75% coverage Definitely for the experiment I was doing. Maybe it was not something crazy but definitely there is influence on science in general, with regards to the experiment.</p> <p>Files\Interview Data\Interview 3.9 1 reference coded, 0.72% coverage</p> <p>Reference 1: 0.72% coverage So I better just get this done quickly and follow the manual like recipe, then I can figure out what I did later on. Which, obviously doesn't give you the best learning experience. Which I think why it's good to have things such as prelab and you can do this quite quickly.</p>
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7.8. Appendix H. Word Frequency Query (Excerpt)

Table 19. Excerpt of word frequency query on prelab interview data

Word	Count	Weight (%)	Similar Words
experiment	196	2.25	experience, experienced, experiment, experimental, experiments, feeling, feels, getting, knowing, knows, seeing
videos	117	1.46	picture, video, videos
prepare	113	1.28	actual, actually, really
understand	101	0.87	develop, developed, developing, educational, machine, machines, makes, making, organic, organise, organised, planning, preparation, prepare, prepared, preparing, ready, setting, settings, training, trainings
useful	72	0.86	quite, rather
prelab	92	0.86	clear, interpreting, reading, realisation, realise, reason, reasonable, seeing, understand, understanding
learn	73	0.78	applied, applies, apply, applying, enjoy, enjoyed, exercises, practical, practice, purpose, useful, using
report	56	0.70	thing, things
theory	56	0.70	prelab
information	101	0.62	check, checking, determine, determined, determining, discovered, discovers, instruction, instructional, instructions, knowing, knowledge, knows, learn, learning, seeing, teach, teaches, watch, watched, watching
manual	95	0.60	become, break, breaking, getting, going, operate, passing, plump, running, sounds, start, started, starting, starts, turned, turning, worked, working, works
demonstrator	63	0.59	first, firstly, start, started, starting, starts
helpful	49	0.59	possible, possibly, theories, theory
cause	43	0.54	difference, different, differently, otherwise
science	44	0.54	session, sessions, sitting
accomplish	40	0.50	manual
chemistry	59	0.50	answer, answered, answering, answers, attended, effect, effective, effectively, issue, issues, result, results, solution, solutions
questions	52	0.49	demonstrated, demonstrator, demonstrators, evidence, present, presentation, presentations, proved, showed, showing, shows
computational	41	0.48	available, helped, helpful, helping, helps, support
explain	57	0.47	cause, effort, getting, makes, making, reason, reasonable
reading	40	0.43	material, materials, stuff, stuffs
physical	61	0.41	aimed, aiming, channel, charge, charged, degree, design, designed, details, direction, directly, guide, guided, guides, level, peaks, place, point, points, showed, showing, shows, stage
discussion	58	0.40	accomplish, accomplished, accomplishing, attain, complete, completely, completion, effect, effective, effectively, fulfilling, manage, managed, management, managing, realisation, realise, skills
write	32	0.40	chemistry

Vita

Education

- The University of Edinburgh, UK, 2016 – 2019
PhD in Chemistry Education
- Utrecht University of Applied Sciences, Netherlands, 2013 – 2015
BEd (propedeutic) in Primary Education
- University of Roehampton, UK, and Charles University, Czech Republic, 2009 – 2010
MA/Mgr (Distinction) in Special Education Needs (Erasmus Mundus)
- Bogor Agricultural University, Indonesia, 1998 – 2005
BSc (Honours) in Chemistry

Research Experience

- **The University of Edinburgh, 2016 – 2019**
Supervisor: Prof Michael Seery
Pedagogical and philosophical validation of undergraduate laboratory education
- **Utrecht University of Applied Sciences, 2013 – 2014**
Supervisor: Jos Derksen
The role of children in educational design and parental involvement of pupils from immigrant background
- **Netherlands Institute for Curriculum Development, 2011 – 2013**
Supervisor: Prof Jan van den Akker
Framework for learning in the context of intercultural exchange projects in secondary education
- **University of Roehampton, 2009 – 2010**
Supervisor: Prof Carrie Winstanley
Inclusive practices in international education
- **Research Centre for Forest Conservation, 2001 – 2002**
Supervisor: Prof Anwar Nur
Renewable alternative energy source derived from *Jatropha curcas* oil

Teaching Experience

- **Demonstrator, 2016 – 2017**
University of Edinburgh
- **Teaching Intern, 2013 – 2015**
Paulusschool, Gooilandschool, Lelyschool, Daltonschool
- **Curriculum Coordinator, 2008 – 2009**
Victory Plus School
- **Teacher, 2006 – 2008**
Sevilla International School
- **Teaching Assistant, 1999 – 2001**
Bogor Agricultural University

Publications

- Seery, M. K., Agustian, H. Y. & Lambert, T. O. (in press), "Teaching and assessing technical competency in the chemistry laboratory", in Seery, M. K. and Mc Donnell, C. (Eds.), *Teaching Chemistry in Higher Education: A Festschrift in Honour of Professor Tina Overton*, Creathach Press, Dublin
- Seery, M. K., Agustian, H. Y., & Zhang, X. (2018). A framework for learning in the chemistry laboratory. *Israel Journal of Chemistry*, 58, 1-9.
- Agustian, H. Y., & Seery, M. K. (2017). Reasserting the role of pre-laboratory activities in chemistry education: a proposed framework for their design. *Chemistry Education Research and Practice*, 18(4), 518-532.
- Seery, M. K., Agustian, H. Y., Doidge, E. D., Kucharski, M. M., O'Connor, H. M., & Price, A. (2017). Developing laboratory skills by incorporating peer-review and digital badges. *Chemistry Education Research and Practice*, 18(3), 403-419.
- Agustian, H. Y. (2016). Redefining disability in the context of 'masyarakat madani', an Indonesian model of inclusive society. *British Journal of Special Education*, 43(4), 358-372.

Conferences and Presentations

- North American Association of Philosophy and Education, University of St Mary of the Lake, 2019, presenting a paper on 'Systematic Review of Research in the Nature of Science, 1963-2019'
- Joseph Black Conference, University of Edinburgh, 2019, presenting a paper on 'Students' learning experience in the chemistry laboratory and their views of science'
- Methods in Chemistry Education Research, Royal Society of Chemistry, 2019, presenting a poster on 'Students' understanding of the nature of science'
- Annual Conference of Philosophy of Education Society, University of Oxford, 2019
- Methods of Research in Science Education, Dublin Institute of Technology, 2018
- Graduate Student Conference: How to conduct a Comparative and International Education (CIE) research project, University of Glasgow, 2018
- Variety in Chemistry and Physics Higher Education Conference, University of York, 2017, presenting a poster on 'Pre-laboratory activities in the undergraduate chemistry laboratory'
- EdD International Summer Seminar, Fontys University of Applied Sciences, 2012, presenting a paper on 'Curriculum internationalisation in secondary education'
- UNESCO School Research Dissemination, UNESCO Headquarters, 2011, on 'UNESCO school network in the Netherlands'
- Erasmus Mundus Special Education Needs International Conference, University of Roehampton, 2010, on 'Inclusive practices in international schools'
- Association of Teacher Education Conference, Charles University, 2010

Awards

- Choral scholarship, University of Oxford, 2019
- Quantitative Methods Masterclass bursary, The University of Edinburgh, 2016
- Choral scholarship, St Mary's Cathedral, 2016
- PhD scholarship, Engineering and Physical Science Research Council, 2016
- Research grant, Stichting Gedachtegoed, Utrecht, 2012
- Erasmus Mundus scholarship, European Commission, 2009

Publications

7.9. Article 1

Reasserting the role of pre-laboratory activities in chemistry education: a proposed framework for their design

Hendra Y. Agustian and Michael K. Seery (2018)

Abstract: In this article we summarise over 60 reports and research articles on pre-laboratory activities in higher education chemistry. In the first section of the review, we categorise these activities as follows. First are those intending to introduce chemical concepts, that typically take the form of a pre-laboratory lecture, pre-laboratory quizzes, and pre-laboratory discussion. Second are those intending to introduce laboratory techniques, that typically take the form of interactive simulations, technique videos, mental preparation, and safety information. Finally, a small number of activities intended to prepare students for affective aspects of laboratory work, in the form of enabling confidence and generating motivation are described. In the second section of the review, we consider a framework for design of pre-laboratory activities that aligns with the principles of cognitive load theory. We propose how the two tenets of such a framework – supporting learners in complex scenarios and provision of information necessary to complete tasks – can be considered for the case of preparing for laboratory learning. Of particular relevance is the nature of information provided in advance and that provided just in time, characterised as supportive and procedural information respectively. Finally, in the concluding section, we draw together the principles outlined in the framework and findings from reports of pre-laboratory work in chemistry to propose five guidelines for those wishing to incorporate pre-laboratory activities into their laboratory curriculum; an activity we argue has a significant literature basis for us to encourage.

7.10. Article 2

Developing laboratory skills by incorporating peer-review and digital badges

Michael K. Seery, Hendra Y. Agustian, Euan D. Doidge, Maciej M. Kucharski, Helen M. O'Connor and Amy Price (2017)

Abstract: Laboratory work is at the core of any chemistry curriculum but literature on the assessment of laboratory skills is scant. In this study we report the use of a peer-observation protocol underpinned by exemplar videos. Students are required to watch exemplar videos for three techniques (titrations, distillations, preparation of standard solutions) in advance of their practical session, and demonstrate the technique to their peer, while being reviewed. For two of the techniques (titrations and distillations), the demonstration was videoed on a mobile phone, which provide evidence that the student has successfully completed the technique. In order to develop digital literacy skills, students are required to upload their videos to a video sharing site for instructor review. The activity facilitated the issuing of digital badges to students who had successfully demonstrated competency. Students' rating of their knowledge, experience, and confidence of a range of aspects associated with each technique significantly increased as a result of the activity. This work, along with student responses to questions, video access, and observations from implementation are reported in order to demonstrate a novel and useful way to incorporate peer-assessment of laboratory skills into a laboratory programme, as well as the use of digital badges as a means of incorporating and documenting transferable skills on the basis of student generated evidence.

7.11. Article 3

A framework for learning in the chemistry laboratory

Michael K. Seery, Hendra Y. Agustian, and Xinchu Zhang (2018)

Abstract: Designing laboratory activities is a real challenge for those working in higher education. There is often an acknowledged frustration with the status quo, but a lack of clear guidance on what strategies might be useful in considering a redesign. This article aims to address the question: what considerations should be taken into account when designing a laboratory activity? To address it, we first describe an overarching framework for laboratory learning, describing it as a complex learning environment. The reason for this is that two clear overarching guidelines emerge – the first is that the laboratory curriculum should be structured so that each new challenge for student is adequately supported by their prior learning so that they can draw on their knowledge to address the new learning situation, and the second is that guidelines for the kinds of preparation for laboratory learning emerge. Based on this framework, we advocate four core principles for laboratory learning that should be considered when designing a laboratory activity regarding the overall purpose, the role of preparation, the teaching of technique, and the consideration of affective dimensions of learning. We illustrate this framework in practice with examples from our own practice, with suggestions on using the literature on laboratory education as a source for curriculum reform within an institution.

7.12. Article 4

Teaching and assessing technical competency in the chemistry laboratory

Michael K Seery, Hendra Y Agustian, and Thomas O Lambert (2019)

Abstract: Teaching chemical technique has a long history going back to Michael Faraday, but assessment of chemical technique is comparatively rare in the modern teaching laboratory. In this work we aim to share our approach on teaching and assessing laboratory techniques. This is grounded in an exemplar-based approach incorporating the principles of formative assessment; whereby students have a known standard, are able to compare their efforts to the known standard, and are able to make appropriate adjustments to their work based on the standard in advance of submission for assessment. We describe the implementation of our approach based on the three components of providing an exemplar, facilitating peer review during activities, and assessment and formal feedback for laboratory competency sessions in Year 1 and Year 2 of our undergraduate programmes. Techniques explored include glassware techniques such as titrations, setting up distillations, preparing standard solutions, as well as instrumental techniques such as UV/vis spectroscopy and gas chromatography. We found that students tended to be highly prepared — likely prompted by the necessity to record their demonstration — and that their levels of knowledge, confidence, and experience improved as a result of the activities. We offer some guidance for others wishing to implement a similar approach in their practice.

7.13. Article 5

Systematic review of research in the nature of science, 1963-2019: Toward pedagogical and philosophical validation of undergraduate laboratory curricula

Hendra Y. Agustian (2019)

Abstract: The nature of science has been set as an essential component in the goals of science education since the nationwide reform in the 1960s, but in reality, its importance and perceived success of curricular implementations are still contestable. Within this pedagogical vis-à-vis philosophical discourse, undergraduate laboratory education appears to escape the intellectual development, despite the common assumption of laboratory being an indispensable element of science education. In this systematic review, 73 empirical studies were analysed in order to establish a case for pedagogical and philosophical validation of undergraduate laboratory curricula, by inquiring into multifarious research designs and instruments used to investigate its many dimensions, its representations in the literature, and pedagogical frameworks underpinning its approaches. Results revealed needs for more deliberation on extracting operable pedagogical approaches from the strong foundation on philosophy of science; more evidence and elaboration on changing misconceptions of the myth of scientific method; and ultimately philosophical validation of undergraduate laboratory curricula.

7.14. Article 6

Students' understanding of the nature of science in the context of undergraduate chemistry laboratory

Hendra Y. Agustian (to be submitted)

Abstract: This research focused on exploring and evaluating students' views of the Nature of Science in the context of undergraduate chemistry laboratory. Thirty-six undergraduate students doing a laboratory course in physical chemistry were assessed using Views of Nature of Science instrument and assessment criteria that categorise them in three levels of understanding. Results revealed that in general, the undergraduate students have transitional views of the nature of science, a level between naïve and informed views. We argue for incorporating the nature of science in undergraduate science curricula. Further substantiation involving an evidence-based pedagogical intervention is needed.

7.15. Article 7

Fine-tuning pre-laboratory activities in support of learning in the undergraduate chemistry laboratory

Hendra Y. Agustian and Michael K. Seery (to be submitted)

Abstract: The importance of pre-laboratory activities in enhancing students' learning in the laboratory has been argued and substantiated. In this paper, we aim to investigate the extent to which the existing pre-laboratory activities facilitate learning in the upper division physical chemistry laboratory. Elicited through a phenomenological approach, the findings are contextualised within a restructured laboratory curriculum, where the element of open inquiry plays an ever slightly more role in the laboratory teaching and learning. We found that students set a high priority on higher order thinking skills through learning goal setting. The awareness of what they can accomplish in the laboratory by preparing for the lab sessions, the affordances to foresee the amount of information they have to manage, and the opportunity to familiarise themselves with new techniques or instruments prior to the actual performance, and the knowledge of how they can go about the data (*e.g.*, calculation and plotting), are some of the aspects pertinent to pre-laboratory work that seem to enhance students' learning experience in the laboratory. The interviews also revealed that in so far as affective domain is concerned, developing confidence in the laboratory is the most important goal set by the students in this study.